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Modelling field hydrology in acid sulfate soil in Nordic conditions with different water management practices

Master's thesis for the degree of Master of Sciences in Engineering submitted for Inspection.

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Abstract of master's thesis

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Abstract

Acid sulfate soils are the nastiest soil type in the world and the soils are located mainly in coast of the Gulf of Bothnia in western Finland. Large share of cultivated fields with acidic sulfate soils are drained because of waterlogging. Increasing of groundwater depth (GWD) by draining fields promotes oxidation of sulfidic materials, and the leaching of acidic water to surface water. Acid discharge from acid sulfate soils has been reported to deteriorate aquatic environment of surface waters. To prevent of acidic discharge formation and maintain GWD, controlled drainage (CD) is implemented. The aim of this thesis was to understand the effect of different water management practices (normal subsurface drainage, CD and CD with sub-irrigation) on GWD and subsurface drain discharge using theoretical description by way of modelling.

During this study, field hydrology of the silty clay loam agricultural field in Söderfjärden, western Finland, with *Sulfic Cryaquepts* soil type was modelled using two one-dimensional models (Drainmod-based model and HAPSU). The model input data were hourly hydrological data from Oct 2010–Dec 2017. The simulation accuracy was assessed graphically as well as by Nash–Sutcliffe model efficiency coefficient (NSE), mean absolute error (MAE) and bias. The models were able to simulate the long-term field hydrological processes with different water management practices. The performance of models for the normal subsurface drainage field was good with NSE value (0.62-0.68) compared with the CD field with NSE value (0.38-0.47). Overall, Drainmod-based model had more satisfactory performance for CD field than HAPSU model.

Comparing the simulated and measured effect of water management practice revealed that not all water flow processes in the field were taken into account in the modelling. The monthly water balance analysis indicated that due to seepage GWD reached the layers below the drainpipe in winter, and deeper GWD was observed after dredging of the main ditch. The simulated drain discharge was clearly affected by water management practices but not seen from the long-term measurements. The models would be good tools for analyzing effects of different water management practices on water quality but the hydrology in the models is needed to be improved and flexibility to implement field operations like dredging and control structure can improve the performance of the models.

Keywords

Acid sulfate soil, Groundwater depth, Drainmod-based model, HAPSU, Water management practices, Water balance, Water quality

Preface

I would like to thank my Professor Harri Koivusalo for providing me with the opportunity to write my master thesis, support for modelling in Matlab, feedbacks during this study period and monthly meetings. I would also like to thank Dr. Seija Virtanen from The Drainage Foundation sr. for all support for providing measurement data from the study site and feedback during this thesis work. I would also like to thank my instructor, Heidi Salo, for all support and feedback during the study period and writing this thesis in university. I really appreciate Heidi Salo's time and support during this thesis to make data analysis. I would like to thank for all members from Water Resources Engineering Group, who supported me when I was stressed and lost during the work.

I am grateful for Drainage Foundation and Finnish Meteorological Institute (FMI) for data in the field and Vaasa weather station and generously providing the data for this thesis work. I would also like to thank Sirkka Tattari from SYKE for providing the HAPSU code. I am grateful to Anna Bonde for the water quality data from ELY center of South Ostrobothnia and grateful to Kari Ylivainio from Luke for crop yield data. I am grateful to Jyrki Nurminen for soil hydraulic parameters. Nevertheless, I appreciate the time and commitment made, unknown to me by name, farmers from fields, who took the regular manual measurement of groundwater depth and pH of drain discharge. I wish to thank Drainage Foundation sr. and Maa – ja vesitekniikan tuki ry. for funding the research.

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List of abbreviations and symbols

Symbols

α	[-]	Albedo
γ	[kPa /°C]	Psychrometric constant
$\triangle$	[kPa /°C]	Saturated vapor pressure
σ	[W /m^2 /K^4]	Stefan-Bolzman constant, 2.043E-10
Θ	[m^3/m^3]	Water content (porosity)
Θ_{res}	[m^3/m^3]	Residual water content
Θ_{sat}	[m^3/m^3]	Saturated water content
α	[m^{-1}]	van Genuchten parameter
ε_1	[-]	Surface emissivity
ε_a	[kPa]	Actual hourly emissivity of the atmosphere
ε_{clr}	[kPa]	Emissivity of a clear sky a value
c_f	[-]	Cloudiness factor (between 0 and 1)
A_{cr}	[m^2]	Cross sectional area of the seepage flow
A_f	[m^2]	Field area affected by seepage
C_f	[m/h]	Capillary flux
d_e	[m]	Equivalent impermeable layers
e^o	[kPa]	Saturated vapor pressure at T_{hr}
e_a	[kPa]	Actual vapor pressure at T_{hr}
ET_t	[m/h]	Actual Evapotranspiration
ET_o	[m/h]	Hourly reference evapotranspiration
G	[MJ /m^2 /h]	Soil heat flux density
h	[m]	Pressure head
i	[m]	Layer number
Kd	[mm/°C/day]	Degree day snowmelt factor
Kf	[mm/°C/day]	Refreezing factor
K_h	[m/h]	Unsaturated hydraulic conductivity
K_s	[m/h]	Saturated hydraulic conductivity
K_a	[m/h]	Saturated hydraulic conductivity above drain depth
K_b	[m/h]	Saturated hydraulic conductivity below drain depth
L	[m]	Lateral spacing between drain pipe
m	[-]	van Genuchten parameter
n	[-]	van Genuchten parameter
P	[kPa]	Atmospheric pressure
pH		Presence of hydrogen ion
q_d	[m/h]	Drainage discharge
q_s	[m/h]	Sub-irrigation discharge/flux
Q_{obs}	[m/h]	Observed discharge
Q_{mod}	[m/h]	Simulated discharge
RH	[%]	Relative humidity
R_n	[MJ/m^2 /h]	Net radiation at grass surface

$R_{l,n}$	[MJ/m^2 /h]	Net longwave radiation
R_s	[MJ/m^2 /h]	Global solar radiation
$R_{S,n}$	[MJ/m^2 /h]	Net short-wave radiation
$R_{L,down}$	[MJ/m^2 /h]	Incoming longwave radiation
$R_{l,up}$	[MJ/m^2 /h]	Upward (outgoing) longwave radiation
$R_{S,down}$	[MJ/m^2 /h]	Incoming shortwave radiation
$R_{S,up}$	[MJ/m^2 /h]	Upward (outgoing) shortwave radiation
T_{hr}	[°C]	Hourly air temperature
t	[h]	Time
u_2	[m/s]	Wind speed at 2 m
u_z	[m/s]	Wind speed at z m
v_a	[m]	Air volume
z	[m]	Depth from ground surface
$\triangle z$	[m]	Soil layer thickness

Abbreviation

1D	One-dimensional
2D	Two-dimensional
3D	Three-dimensional
AASS	Actual acids sulfate soil
AS	Acid sulfate
CD	Controlled drainage
CDI	CD with sub-irrigation
DD	Drain discharge
FAO	Food and Agricultural Organization of the United Nations
FMI	Finnish Meteorological Institute
GWD	Groundwater depth
IN	Infiltration of precipitation
ND	Normal drainage
NSE	Nash-Sutcliffe efficiency
MAE	Mean absolute error
PASS	Potential acid sulfate soil
PET	Potential evapotranspiration

1. Introduction

1.1. Acid sulfate (AS) soils

Dent and Pons (1995) mentioned acid sulfate (AS) soils as the nastiest soil type in the world, as they generate the sulfuric acid that lowers the pH of soil water. AS soils are present around the globe, specifically found in coastal areas and floodplains. Approximately 20 million ha of AS soils are located in coastal and tidal swamps worldwide (Burton et al., 2006). These waterlogged swamps and coastal plains are reclaimed for agricultural purposes with field drainage to exploit expected nutrients content to make the soil more fertile but impact of nutrients on crop production is seldom noticed (Dent and Pons, 1995). Draining swamps and coastal plain can oxidize the potential AS soils there. Ripe and oxidized AS soil affect the quality of soil water. The soil becomes acidic, as large volumes of acid are stored in the soil (e.g., Burton et al., 2006; White et al., 1997). The acidic discharge occurs after the rate of the acid production from soil layer limits the buffering capacity of the soil (Dents and Pons, 1995). Formation of acidic water has the potential to dissolve toxic metal into drained water. Acidic discharges from AS agricultural soils to streams, rivers or lakes have the adverse impact on the growth of vegetation and aquatic life and deteriorate the quality of groundwater used for drinking purposes (Dent and Pons, 1995; White et al., 1997). According to White et al. (1997), many Australian coastal floodplains with drained AS soils had caused the corrosion of engineering structures as well as the massive death and increase diseases of fishes. Earlier studies (e.g., Dent and Pons, 1995, Stauber et al., 2016) have shown that acidic discharge possibly can be minimized by keeping the groundwater depth (GWD) above the sulfide bearing soil layer that prevents oxidation of sulfides. According to White et al. (1997), sulfidic wetland should not be drained until the suitable methodology is available to treat acidic discharge.

Draining water from AS soils and lowering the GWD cause soil ripening and oxidation of sulfidic materials which changes the physical (Pons and Zonneveld, 1965) and chemical properties (Dent and Pons, 1995) of the soil. The ripening of the soil creates irreversible cracks (Pons and Zonneveld, 1965). In most cases, the ripening and oxidation of AS soils are caused by anthropogenic activities like drainage, dredging, and excavation (Stauber et al., 2016). These activities can create permanent cracks in AS soils. Past studies (e.g., Dent and Pons, 1995; Virtanen et al., 2014) have shown that the saturated hydraulic conductivity of acidic sulfate layers changes over time in agricultural fields. The changes in soil hydraulic conductivity are likely due to changes in soil structure i.e. formation of the cracks and larger soil pores.

AS soils have sulfidic materials and when drained or exposed to aerobic condition forms sulfuric acid. The soil layer holding pyrite or other iron sulfide minerals and oxidizes in aerobic condition and forms sulfuric acid through oxidation and acidity through hydrolysis (Soil Survey Staff, 2014). In anaerobic conditions, bacteria and microorganisms decompose organic matter, which lowers the concentration of sulfate

(SO_4^{2-}). The biological process takes place in the tidal swamp and marsh, where iron (Fe) oxides are form particulate matter in sediment. After the chemical and biological processes, the final product is pyrite (FeS_2). Sulfidic materials are stable in anaerobic conditions (Soil Survey Staff, 2014). The problem arises when pyrite or sulfidic materials are exposed to aerobic conditions (Equation 1a). After the oxidation of pyrite, the next step is oxidation of iron ion (Fe^{2+}) to (Fe^{3+}) and its hydrolysis generates hydrogen ions lowering pH of water. The overall oxidation and hydrolysis of Sulfur (S) and Iron (Fe) of pyrite and iron monosulfides are presented in Equation (1b) (e.g., Dent and Pons, 1995; White et al., 1997) and Equation (2) (Boman et al., 2016) respectively.

$$\begin{aligned} &FeS_2(s)\{pyrite\} + \frac{7}{2}O_2(aq)\{oxygen\} + H_2O\{water\} \\ &\quad \rightarrow Fe^{2+}(aq)\{\text{ } soluble\ iron\ II\ ion\} \\ &\quad + 2SO_4^{2-}(aq)\{sulphate\ ion\} + 2H^+(aq)\{hydrogen\ ion\} \end{aligned} \tag{1a}$$

$$\begin{aligned} &FeS_2(aq)\{pyrite\} + \frac{1}{4}O_2(aq)\{oxygen\} + \frac{3}{2}H_2O(aq)\{water\} \\ &\quad \rightarrow FeO.OH(s)\{ochre\} + 2H_2SO_4(aq)\{sulfuric\ acid\} \end{aligned} \tag{1b}$$

$$\begin{aligned} &FeS(aq)\{iron\ monosulfides\} + \frac{9}{4}O_2(aq)\{oxygen\} \\ &\quad + \frac{3}{2}H_2O(aq)\{water\} \\ &\quad \rightarrow FeO.OH(s)\{ochre\} + H_2SO_4(aq)\{sulfuric\ acid\} \end{aligned} \tag{2}$$

The oxidation products are leached to watercourses mainly due to autumn rainfalls or snow melting after the GWD is raised above drainpipes. Ferrous iron ($Fe^{2+)}$ oxidizes to ferric iron (Fe^{3+}) and precipitate easily when dissolved in water whereas sulfate ion (SO_4^{2-}) are leached to watercourses. Depending on the soil composition, the metal ions are dissolved with acid and acids are buffered with soil before released to drained water (Dent and Pons, 1995). The metal ions in drainage water will be further oxidized downstream, which results in depletion of oxygen in the surface water. After the complete reactions of the pyrite, hydrogen ions are generated (White et al., 1997). Hydrogen ions drops pH of discharge water. Due to different dissolved metal ions and pH fluctuation in discharge water, a synergistic toxic effect could arise in receiving water bodies like lake, river or sea. The decrease of dissolved oxygen (DO) level below 5 mg/l in streams causes aquatic life to be under stress and if DO level is below 1-2 mg/l in water bodies for few hours, it can result in the loss of larger fish (MPCA, 2009). End products after the complete oxidation process of sulfidic materials are difficult to assume since the process can be broken down into further pathways with oxygen along its flow path and the rate of oxidation depends on field hydrology, how the soil is drained and the climatic condition. The complete oxidation of sulfidic sediment can range from tens to hundreds of years dependent on the rate of oxygen movement (White et al., 1997). Water quality studies from, AS soils are important to determine the impact of drainage on the natural buffering capacity of receiving waters and aquaculture of water bodies (Lambert et al., 1983).

In Finland, AS soils are located mainly in the coastal area of the Baltic Sea and eastern Finland (Yli-Halla et al., 2017). Due to isostatic soil uplift above sea level in the coastal area of the Baltic Sea (Österholm et al. 2015), a large area of the sulfidic sediment region is in agricultural use (Yli- Halla et al., 1999). The presence of iron monosulfides (FeS), AS soil type, is common in the coastal areas of Finland. Hypersulfidic materials as dark-colored soil refer to the presence of iron monosulfides (Boman et al., 2016). AS soils have been used for cultivation in Finland for many decades, leading to the long-term leaching of acidity to surface waters (Joukainen et al., 2003). With Soil Taxonomy categorization, AS soils used for cultivated fields in Finland range from 2–6% of total field area and 13% of total cultivation soils are AS soils, if criteria of subsoil pH < 5.0 is applied (Yli-Halla et al., 1999). The sulfide bearing soil horizon is typically lying below the depth of 0.5 m in most cultivated AS soils, but their presence can be found even below 1 m (Yli-Halla et al., 1999). Most of the agricultural fields are subsurface drained and the drain depth is typically around 1–1.2 m (Joukainen and Yli-Halla, 2003). As a result of artificial drainage in AS soils, the amount of total dissolved metal discharge from AS soils to rivers is higher than from entire Finnish industry (Roos and Åström, 2005; Åström and Bjöklund, 1995). Discharge from AS soils possesses a risk to tens of rivers and the deaths of vegetation and fish have been reported in rivers of western Finland (Toivonen, 2013; Joukainen et al., 2003). The pH of the river water was dropped rapidly with increased agricultural subsurface runoff from AS soils (Toivonen, 2013). Failure in the fish reproduction was noted in Larsmo Lake in Finland but it might also be due to climate change in areas with AS soils (Toivonen, 2013).

1.2. Field drainage

Artificial drainage is used for the reclamation of naturally waterlogged lands for agricultural purpose as well as to improve the drainage of existing agricultural fields (e.g., Burton et al., 2006; Lambert et al., 1983). High soil water content during the growing season can have a negative impact on the crop yield if waterlogging causes shortage of air in the root zone (Lambert et al., 1983). According to Lambert et al. (1983), if air volume drops below 10 % of total porosity, aeration in the root zone becomes inadequate for crops. In the humid and cold part of North America and Europe, seasonal waterlogging is a common problem as annual precipitation is always higher than annual evapotranspiration, whereas evapotranspiration typically exceeds precipitation during the growing season (Lambert et al., 1983). Field drainage can be implemented with subsurface or surface drainage. In humid and cold climate zones, field drainage is used to remove excess water from the root zone during the growing period, but also during heavy rainfall in autumns in order at the time of the harvesting to achieve good soil structure for agricultural condition (Lambert et al. 1983; Skaggs et al., 1995).

In Nordic conditions, it is important to remove the excess water from soil profile through subsurface drainage during the snowmelt. The beginning of the cultivation period depends on snowmelt timing in spring (Jin and Sands, 2003). The impact of subsurface drainage on the quality and quantity of discharge water depends upon the drainage density, soil properties, topography and boundary conditions of the agricultural field. Based on the installation of drainage, on average, 25–35% of annual precipitation is drained through subsurface drainage (Jin and Sands, 2003). Most of the drainpipes installed in Finland are with the depth of 1 m and drainage spacing of 10–14 m for silty and silty clay loam soil (Paasonen-Kivekäs, 2009).

In Nordic conditions, effective drainage is the prerequisite for cultivation field. Kosunen (2012) presented an example, where the drainage water was mainly conveyed to open drains and overall 13% of the field area water was discharged straight to surface water bodies. Field drainage changes water flow pathways in the field but also affects the quality of receiving water bodies where the drainage water is conducted. The criticism was observed around the globe, as the drainage of agricultural land is the potential non-point source for nutrient loads to surface water ecosystems and one of primary causes for surface water quality problems (Evans et al., 1995). However, subsurface drainage has increased the leaching of nitrogen and phosphorus from the field compared with surface drainage (Gilliam and Skaggs, 1986). In addition to the nutrient loss, acidic discharge from the AS soil field has the potential to affect the water quality of drain discharge (DD) (Dent and Pons, 1995).

In Finland, two water management practices are used for maintaining GWD above the sulfide bearing soil to delay the oxidation of sulfidic materials and reduce the volume of acidic discharge from AS soils: (1) controlled subsurface drainage (CD) and (2) controlled subsurface drainage with sub-irrigation (CDI). In CD, a weir is used for managing GWD in the field (Figure 1; Bärlund et al., 2005). In CDI, a weir is used, and water is pumped to raise GWD. Both water management practices have been used for a long time with the objective to reduce nutrient loading to surface waters (Gillian and Skaggs 1986), maintain GWD for enhancing crop growth, and in AS soil to reduce the release of acidity and metals (Palko, 1994; Bärlund et al., 2005; Virtanen et al., 2016). Field for CD needs to be flat with the slope of less than 0.5% and must be systematically drained with subsurface drainage (Evans et al., 1995). CD reduces mobilization of solutes and salt below the root zone, which reduces the negative impact to surface water environment (Bärlund et al., 2005). CD has received much attention on AS soil, but the significant impact is not visible on the environment due to by-pass of groundwater flow (Toivonen, 2013). Installation of plastic sheet was recommended (Österholm and Rosendahl, 2012; Toivonen, 2013) to control the by-pass flow in AS soil in Finland but there are not enough studies carried out to identify the impact of plastic on bypass flow.

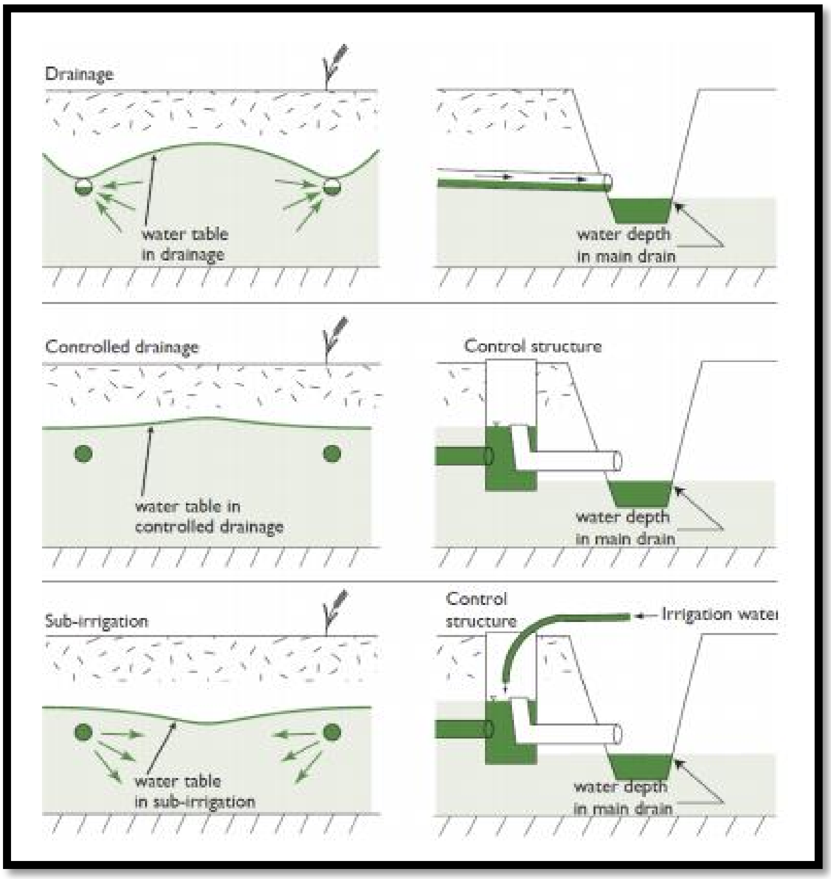

Figure 1. Illustration of principle and water flow in the soil profile of normal subsurface drainage (ND), controlled drainage (CD) and CD with sub irrigation (CDI) (Peltomaa- Kivekäs, 2009, p. 318).

1.3. Modelling field hydrology

Process-based hydrological models (e.g., Drainmod, Hydrus, SWAP, and FLUSH) are regularly used to study field hydrology and soil water balance (e.g., Morrison et al., 2014; El-Sadek et al., 2001; Turunen et al. 2013). The Drainmod model has been noted to simulate subsurface drainage for cold climate conditions (Morrison et al., 2014). Combined with field data, models are effective tools to identify factors and processes that control the field hydrology (Morrison et al., 2014). Drainmod uses Hooghoudt drainage equations that are based on steady-state assumption of soil moisture distribution. Other models (Hydrus, SWAP, and FLUSH) simulate DD with unsteady state approach based on Darcy Law. Model complexity depends on how the spatiality of the simulated domain is considered. In 1D models, the simulated area is represented with a soil profile where water moves in the vertical direction, but not in the horizontal direction. Two (2D) and three-dimensional (3D) models simulate also horizontal water flow in the soil profile and can consider the spatial variation in the field area. However, 2D and 3D models requires more data for the model parameterization. Therefore, 1D models are widely used to study drainage and irrigation practices and crop growth in different soil types (Morrison et al., 2014; El-Sadek et al., 2001; Singh et al., 2006). Winter conditions are typically taken into account in the models by incorporating a sub-model for snow accumulation, melting and refreezing. The snow model can be simple degree-day-model (e.g., Koskela et al., 2012) or energy-balance based model (e.g., Hutka et al., 1996). Process-based hydrological models linked with the water quality model (HAPSU, SMASS) are used for simulating water quality of discharge water from the AS soil field (Bärlund et al, 2004, Bronswijk et al., 1994). Chemical models consist of water flow sub-model, pyrite oxidation, oxygen transport sub-model, and solute transport sub-model (Bronswijk et al., 1994).

In Finland, 1D HAPSU model, was used to simulate water flow and quality of drain discharge in Nordic conditions for agricultural fields with AS soil (Bärlund et al, 2004). HAPSU model simulates snow accumulation and melting with the energy-balance sub model. The model includes routine for CD, lime filter drainage (Bärlund et al., 2004) but lacks CDI. The HAPSU model was applied in IImajoki and Mustasaari experimental fields by Bärlund e al. (2004; 2005). Väisänen (2014) used Drainmod for studying the effect of submerged weirs in the main ditches on GWD in a field with ND. Based on Drainmod simulations in Soderfjärden (Väisänen, 2014) the damming in main ditch decreased dropping of the GWD in ND field. However, it has not been studied with simulation models, if the effect of the water management practices would be more effective in maintaining GWD above sulfide bearing soil layer. Moreover, simulating field hydrology with CD with HAPSU model in AS soil in cold climate has been reported in the literature (Bärlund et al., 2004) but other models have not been documented.

1.4. Scope and objectives

Hydrological modelling together with measurements has been used for studying the agricultural field hydrology (Häggblom, 2017; Turunen et al., 2013). The water balance approach for the agricultural field with simulated variables is a common method for understanding the field hydrology (e.g., Häggblom, 2017). In this study, the effect of three water management practices (ND, CD and CDI) on field water balance and water quality of DD in AS soils was simulated over seven-year period (Oct 2010-Dec 2017). Simulations were carried out with the Drainmod-based model and hydrological part of HAPSU model. The HAPSU model was used also for simulating water quality of DD in the field with ND, CD, and CDI. The Drainmod based model was calibrated and validated against hourly measured output variables (GWD and DD). The study aimed to distinguish the effect of drainage practices on field water balance and GWD. The Drainmod-based model was tailored for study site properties, including deep seepage towards the main ditch. The Drainmod-based model was used due to its applicability to simulate field hydrology and Drainmod (Skaggs, 1978) has been widely applied in different soil type and cold climate condition (Morrison et al., 2014). However, Drainmod has not been applied in AS soils. Another aim of the study was to compare Drainmod-based model simulation results with HAPSU model simulations. HAPSU model was developed for simulating field hydrology in AS soil agricultural field in Nordic conditions. The HAPSU model enabled simulation of DD quality that is not included in the Drainmod-based model. The aim was to detect if simulations with the two models combined with field data can shed light into the factors controlling water flow in the Söderfjärden field.

The specific objectives of this thesis were:

1. To calibrate and validate the Drainmod-based model against hourly GWD observation and measured DD for ND field and test the simulated effect of CD and CDI practices on field hydrology.

2. To understand hydrological behavior of the field with different management practice using data analysis and modelling.

3. To study the hydrological impact of field operations (e.g., dredging the main ditch and control structure) on GWD and DD.

4. To test the performance of the HAPSU model (hydrological part) and simulate drain discharge quality in ND, CD and CDI field.

2. Materials

2.1. Site description

The Söderfjärden experimental field (Figure 2) is located in Vaasa, about 6 km from the Gulf of Bothnia coastline, in southern Ostrobothnia, (62 59’ 53.23’’ N, 21 36’ 16.94’’ E). The field has silt clay loam soil classified as *Sulfic Cryaquept* (Soil Survey Staff, 1999). The area is an old meteorite crater (2300 ha), the fields are residing about 2 m above the sea level with sulfide - bearing marine sediment. The Söderfjärden field was drained with open drains and the area was poldered to form arable land. The pumping station was built in 1926 because one tenth of Söderfjärden was below sea level. In 1950s, the field was subsurface drained (Österholm et al. 2015). The subsurface drainage of the study field was renewed in the 1990s and equipped with control wells to enable regulation of drainage. Subsurface drainage waters from fields are conveyed to the main ditch on the northwest border of the field. The main ditch had a depth of 2.7 m (red line in Figure 2, Österholm et al., 2015).

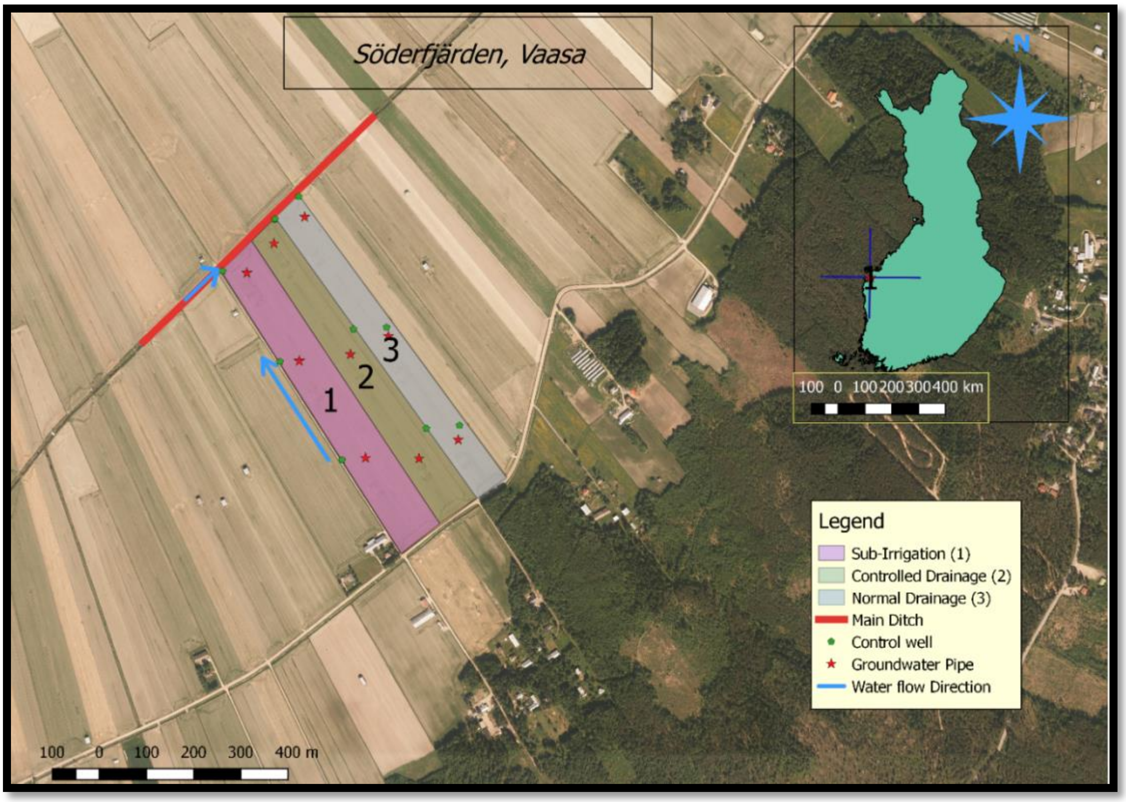

Figure 2. The location of Söderfjärden experimental field in Western Finland. The water management practices of the experimental field sections with 1) controlled drainage with sub irrigation (CDI), 2) Controlled drainage (CD) and 3) normal drainage (ND) practice. Blue arrow indicates water flow direction in the field and the main ditch. Map source: National Land Survey, Finland.

The study field was divided into three experimental field sections (Normal drainage (ND), Controlled drainage (CD) and CD with sub-irrigation (CDI)). The total area of the experiment field is 18.4 ha and each field section is 80–100 m wide and 710–740 m long. The field has a slope of 0.14%. The sections have separate subsurface drainage systems

(Figure 3). The subsurface drain pipes were installed at the depth of 1.1 m. The drain spacing varies between 35–50 m. Each field section was divided into three subsections that have their own control wells (see Figure 3). The collector pipe for the laterals was at the depth of 1.3–1.5 m. Drain discharge (DD) was measured from each of the field sections at the outlet of the low section control well (northwest border of the field) and before conveying the drainage water into the main ditch.

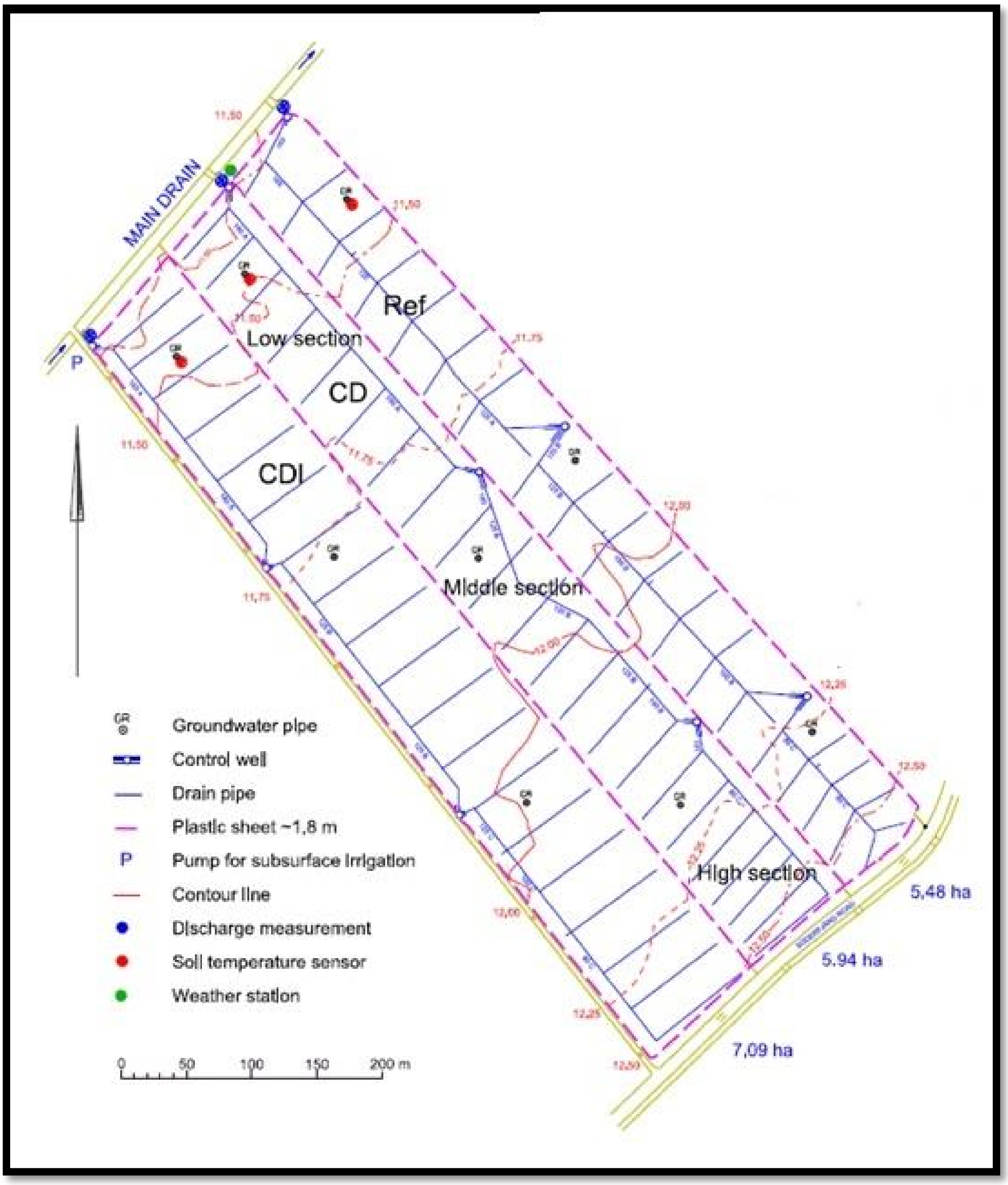

Figure 3. Layout of the Söderfjärden experimental field with subsurface drain (blue line) drainage and monitoring systems. The area of the experimental fields sections are separated by plastic sheet which is denoted by pink dash line and subsection of the field section (low, middle and high) is labeled. Red dash line indicates elevation of the field. (Modified from Österholm et al., 2015)

Plastic sheets were installed between field sections in June 2010 to prevent soil water flow between the field sections. The vertical plastic sheets start from the depth 0.3 m beneath the soil surface and go down to the depth of 1.8 m.

2.2. Data description

2.2.1. Meteorological data

The research site was equipped with measurements of meteorological variables (green mark in Figure 3). The online measurements were started in October 2010. Hourly precipitation and air temperature were recorded at the field site starting from October 2010. Wind speed, air temperature, precipitation, global radiation, relative humidity, and snow depth from were available from the Finnish Meteorological Institute (FMI) weather station in Vaasa (10 km from the study site). The annual average measured meteorological variables from the field station and FMI are presented in Table 1.

Table 1. Minimum, mean and maximum annual air temperature, mean annual humidity, mean annual wind speed and annual precipitation Söderfjärden 2011-2017.

	Minimum Air temperature (°C)	Mean Air temperature (°C)	Maximum Air temperature (°C)	Precipitation (mm/a)	Mean Wind Speed (m/s)	Average Humidity (%)
2011	-22.3	5.9	23.9	469	4.2	81.7
2012	-23.7	4.3	21.7	579	4.1	82.2
2013	-16.6	5.9	21.1	584	4.3	80.2
2014	-20.4	6.0	24.2	716	4.1	81.6
2015	-13.5	6.4	21.1	637	4.5	82.7
2016	-23.3	5.2	21.9	686	3.9	83.3
2017	-16.4	5.2	19.0	532	4.1	82.3

The annual average air temperature varied from +4.3 ℃ to +6.4 ℃ during the study period. The annual precipitation was 650 mm and on average rainfall occurred 7.5 days per month (Bärlund et al., 2004). Over 50% of the total precipitation occurred between July and October (Figure A1 in Appendix A). The maximum snow depth was 68 cm during the study period (2010-2017). The snow cover typically lasted from mid-December until mid-April (FMI, 2018). The annual precipitation in 2014 and 2016 was higher than average annual precipitation of 650 mm because 30 % of the annual precipitation was recorded in August in these years, which was higher than other years (Figure A1 in Appendix A). Daily metrological variables observed in Sörderfjäden are presented in Figure 4.

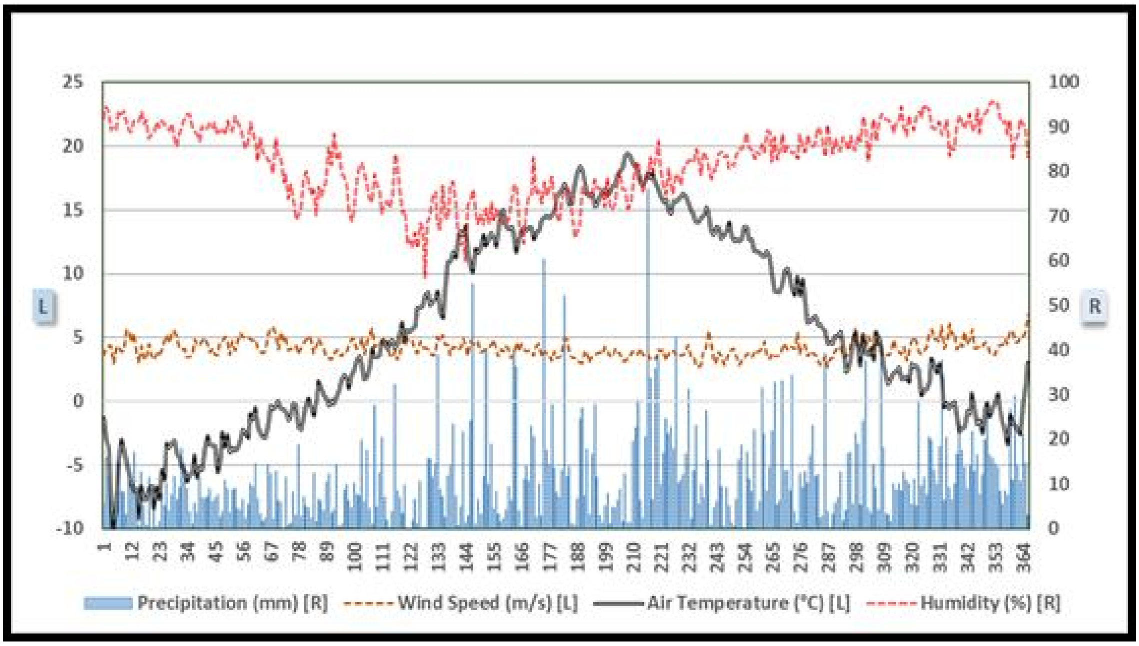

Figure 4. Average daily air temperature (°C), average precipitation (mm/d), wind speed (m/s) at 10 m, and relative humidity from FMI station in Vaasa. Average year is calculated from periods 2011-2017. L vertical axis is for air temperature and wind speed. R secondary vertical axis is for precipitation and humidity. Lateral axis indicates the day of the year.

2.2.2. Hydrological field data

Each field section has its own automatic measurement stations that is located at the lower subsection closes to the main ditch (Figure 3). The measurement started in October 2010 and included groundwater depth (GWD), drain discharge (DD), and water quality variables (pH, conductivity, and soil and water temperature) which all were logged at 10-minute (time) interval. Addition to automatic GWD measurement, manual GWD observations were made using three perforated groundwater tubes installed at each of three subsections (low, middle and high) in each field section (see Figure 3). Manual GWD observations tubes were installed at the depth of 2.5 m. The floating antenna was used to manually measured GWD (Österholm et al. 2015). The antenna is a plastic pipe attached to a foam floater with a height of 30 cm. The antenna sinks 30 cm below GWD and GWD can be calculated as Equation (3) (Österholm et al., 2015).

$$GWD = A_l - A_t - 0.30 \qquad (3)$$

where *GWD* (m) is the groundwater depth, A_l (m) is the total length of antenna, and A_t (m) is the length of antenna above the soil surface.

Water velocity in the pipe was measured with Fluxus 5107 ultrasonic device (Österholm et al., 2015). The discharge was computed based on the velocity and diameter of the EHP sensor pipe. Water quality variables were measured automatically (pH, water conductivity, temperature) and manually (pH) from the DD. Manual measurements were conducted on average 10 times in a year, mainly during May–December. Surface runoff was not measured at the field (Österholm et al. 2015).

There were only small differences in the measured annual (see Table 2) and monthly (see Figure 5) discharge between the ND and CD field. On average, the measured DD from the CDI field was 17.4% lower than DD from the CD field (Figure 5 and Table 2). The highest DD was measured at CD field. The measured DD from the CD field section was higher than the ND field. The maximum DD was recorded in April likely due to snowmelt. In the year 2012, the annual DD in the CDI field was higher than ND field because of water pumped (50 mm) in the CDI field (Table 2). The total volume of pumped water over the seven years study period was 141 mm.

Table 2. Annual average groundwater depth and cumulative measured drain discharge for subsurface irrigation field (CDI), controlled subsurface drainage (CD) and normal surface drainage (ND) field.

	Average Groundwater Depth (m)			Drainage Discharge (mm/a)		
	ND	CD	CDI	ND	CD	CDI
2011	1.19	1.18	1.01	252	281	239
2012	1.12	1.06	0.90	294	332	301
2013	1.16	0.99	1.07	269	268	225
2014	0.96	0.92	1.00	340	322	245
2015	1.16	1.08	0.83	325	357	286
2016	1.21	0.98	0.72	255	265	204
2017	1.12	1.22	0.98	252	234	202
Total	1.13	1.06	0.93	1990	2062	1704

The average annual GWD was below drain depth (1.1 m) during most years for both ND and CD field, whereas in the CDI field average GWD was higher than drain depth. Figure 5 shows that the monthly GWD was below drain depth in February and in June to October in the ND and CD field.

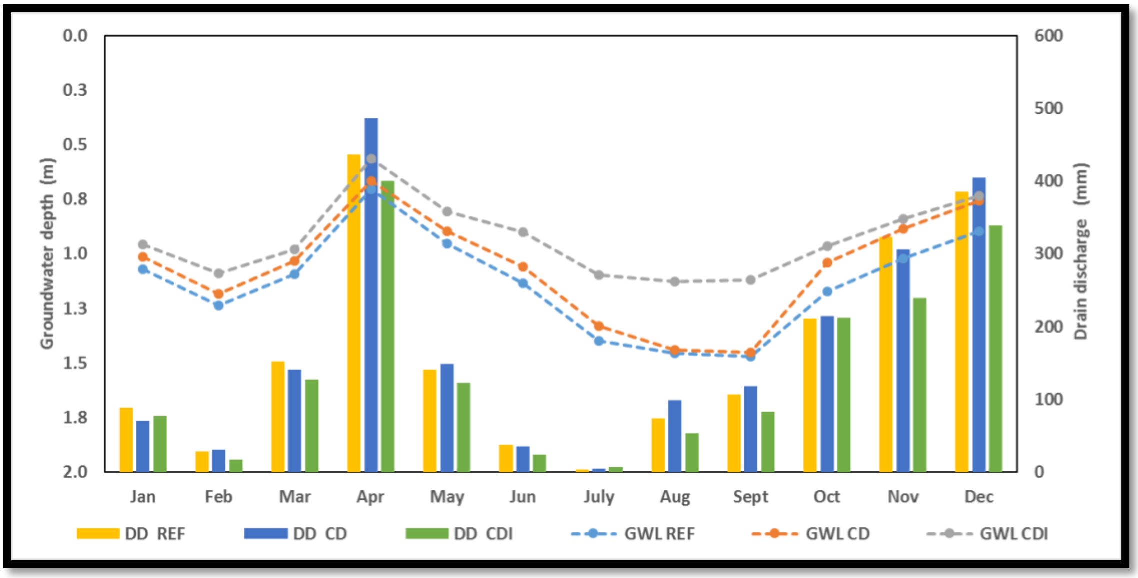

Figure 5. Monthly average groundwater depth (m) from automatic measurements and measured cumulative drain discharge (DD) from subsurface irrigation field (CDI), CD field (CD) and normal drainage field (ND).

The monthly DD from the CD field was higher than the CDI field (Figure 5). Most of the DD occurred in April, November, and December from each field section with monthly share of 25, 15 and 20 %, respectively, of total annual DD. The lowest monthly DD and largest GWD occurred in June till August.

2.3. Soil properties

According to Yli-Halla (2012), soil profile close to the experimental field could be divided into five soil horizons by their morphological characteristics (Table 3). The texture of topsoil (0–30 cm) was silty loam and layers below it was silty clay loam. In Finland, according to Eden et al (2012), actual acid sulfate soil (AASS) is categorized as soil with pH < 4.0 because of the oxidation of sulfides and soil samples are measured directly from oxidized sediments. Potential acid sulfate soil (PASS) is defined as soil with sulfur in the form of sulfides, which are not oxidized, soil sample with pH > 6 and sulfur percentage higher than 0.2%. The color of jarosite (hydrous sulfate of potassium and iron) was observed in layer 28- 86 cm and horizon 86-152 cm was reported to meet the requirement of a sulfuric horizon which has already oxidized and that was known as AASS. The soil layer below 140 cm contained total sulfur percentage higher than 0.2 and pH > 6 therefore, the soil layer was defined as PASS. In this study soil depth below 1.4 m was identified as critical soil layer with high potential of oxidation of the sulfidic material in future.

Table 3. Physical and chemical soil characteristics of the Söderfjäden experimental field adapted from Yli-Halla 2012, Österholm et al., 2015.

Layer	1	2	3	4	5	Ref
Depth (cm)	0–30	30–50	50–100	100–150	150–280	
Horizon	Ap	Bgj1	Bgj2	Bg	Cg	1
Texture	Silty Loam	Silty Clay Loam	Silty clay loam	Silty clay loam	Silty clay loam	1
Clay (%)	26	38	36	38	40	1
Silt (%)	68	65	60	64	61	1
Sand (%)	6	3	0	1	1	1
pH (H_2O)	6.7	4.7	4.0	3.8	7.9	2
Al (mol/m3)	1.35	10.53	20.53	10.53	1.35	2
Fe (mol/m3)	0.7	0.7	-	-	-	2
SO_4-S (mg/kg)[2]	17.2	15.3	592.0	409.0	729.0	2
S tot (%) (Sulphur)	0.23	0.35	0.39	0.83	0.79	1
Ks (m/h)	-	4.3×10^{-4}	1.5×10^{-4}	-	-	3

1 = Yli-Halla (2012), 2 = Österholm et al. (2015), 3= Table A1 in Appendix A

Saturated hydraulic conductivity of the 2nd and 3rd layers (Table A1 in Appendix A) was determined according to the method of Klute and Dirksen (1986) at water laboratory of Aalto University.

3. Methods

3.1. Drainmod-based hydrological model

Drainmod (Skaggs, 1978) is a mathematical model that simulates the main hydrological process of the poorly drained field with a shallow groundwater table. The model simulates soil water movement and groundwater table with hourly or daily time step. The model has been applied for agricultural (Morrison et al., 2014) and forest (Tian et al., 2011) water management simulations. The model computes drainage rate based on the assumption that lateral movement occurs in saturated soil. The model simulates controlled drainage (CD) and sub-irrigation (CDI) system (Wahba et al., 2002) and includes description for nitrogen cycle processes (Youssef et al., 2003; Tian et al., 2011), and has been applied to study the effect of field drainage on nitrogen leaching, and drainage for salinity control (Youssef et al., 2003; Kandil et al., 1992).

The Drainmod-based model that was applied and developed further in this thesis is the hydrological model used for academic work (Koivusalo and Kokkonen, 2003; Karvonen et al., 1999). It uses a similar principle to Skaggs (1978) and the Drainmod model. The drainmod-based model calculates the water balance (Figure 6) of the soil profile with Equation (4). The one-dimensional soil profile was bounded in the horizontal direction by the drain line and midpoint between the drain pipes. In the vertical direction, the boundaries were from the impermeable layer up to the soil surface. Precipitation is initially stored at the soil surface where it infiltrates into the soil profile.

$$\triangle W_a = t_d(DD + ET_t + SR + S - P - Pump) \tag{4}$$

where $\triangle W_a$ (m)is the change in soil water storage, DD (m/h) is drain discharge, ET_t (m/h) is actual evapotranspiration, S (m/h) is seepage from the soil, P (m/h) is precipitation, $Pump$ (m/h) is pumped water, and t_d (h) is the computation time step.

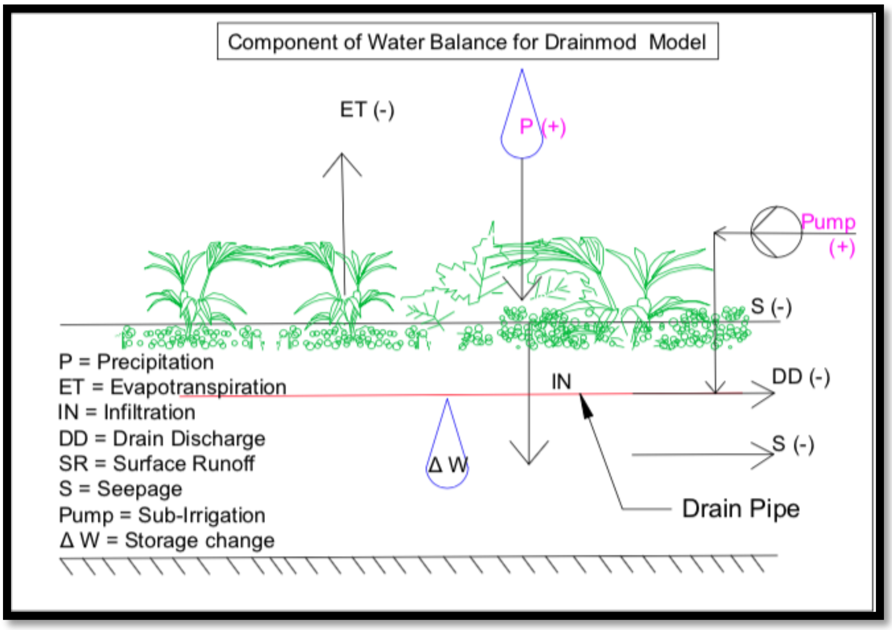

Figure 6. Water balance components of Drainmod-based Model. Components with pink label present water input and black labels present water outflow from the soil.

A Drainmod-based model was implemented and run in Matlab. The Drainmod-based model solves air volume dynamics in a soil column. The model uses the water balance of soil profile in terms of air volume instead of water volume stored in the soil. Based on this concept water can infiltrate to soil profile if there is air filled pore space in soil. Air filled pore spaces are generated as the water balance outflow components remove water from the soil domain. Air volume in the soil was calculated with the assumption of static steady-state conditions for the soil moisture distribution (Skaggs, 1978). A degree-day snow model (Koskela et al. 2012) was coupled with the Drainmod-based model. The snow model uses air temperature to calculate snow accumulation and melt at the soil surface.

Surface runoff occurs when rainfall or snowmelt discharge on the soil surface is higher than infiltration capacity or if water input exceeds the empty pore space in the soil profile. Surface runoff is delayed if the water input on the soil surface is higher than soil infiltration capacity and flows overland before discharged to ditch or stream.

3.2. HAPSU model

The 1D ionic flow model, HAPSU (Ionic Flow Model for Acid Sulfate Soils) was developed in the 1990s to simulate water quality and quantity of drain discharge (DD) for both acid sulfate and non-acid soils in boreal conditions (Hutka et al., 1996). The HAPSU model has been tested in AS fields (Ilmajoki and Mustaasari) in Finland where Bärlund et al. (2005) simulated field hydrology and hydrochemistry of DD. The model considers the cold climate/winter conditions with energy balance snow model that simulates snow accumulation, melting and freezing of water in a snowpack. Evapotranspiration occurs from soil, depression storage at the soil surface or directly from snow cover (Bärlund et al., 2005). Water flow in the soil is simulated with the Richards (1931) equation with laminar flow assumption and DD with the Hooghoudt (1940) equation. The model has routines for simulating CD and lime filter (Hutka et al., 1996). The HAPSU model estimates water quality parameters like pH, the concentration of sulfate, hydrogen ion, iron, calcium, and aluminum. Cation exchange, oxidation, reduction, dissolution, and weathering are reactions incorporated into the model (Hutka et al., 1996).

The major input variables for HAPSU model were daily precipitation, daily air temperature and the five-day cumulative sum of PET. The snow sub-model was based on the energy and water balance approach (Vehviläinen et al., 1992). The model simulated soil shrinking and swelling based on the changes in water content. The porosity of the soil is not constant but changes with the water content. The change in soil pores was simulated with shrinkage curve (Hutka et al., 1996).

The computation of pH of soil water is based on ion exchange equilibrium between water and exchange complex reaction (Vries et al., 1989). The acid released due to the oxidation reactions will be partially neutralized with various buffer mechanism depending on soil properties (Dent and Pons, 1995). If pH of pore water drops below 3 and ranges from 3-

4.8, the iron and aluminum minerals respectively buffer pH and dissolve into the pore water. In extremely acid soil, cation exchange of hydrogen ions against basic cations at the exchange complex will buffer the pH of the pore water causing leaching of basic cations and acidification of soil. The chemical part of the model requires information about both field hydrology and soil properties (Hutka et al., 1996). The HAPSU model could be suitable for comparing the effectiveness of CD and lime filter drainage practices on quantity and quality of DD if hydrochemical and geochemical field data exits (e.g., Bärlund et al., 2005). The sub-irrigation sub-model is needed for HAPSU model and in some study, sub-irrigation was implement by increasing the precipitation as implemented (Kosunen et al., 2012).

3.3. Numerical model

3.3.1. Computation of potential evapotranspiration

Potential evapotranspiration (PET) is the amount of evapotranspiration from a large area of uniform vegetation cover (e.g., grass) under conditions not restricted by water supply in the soil (Allen et al., 1998). Potential evapotranspiration is calculated with reference evapotranspiration (ET_o), which characterizes "a hypothetical reference crop with an assumed crop height of 0.12 m and fixed surface resistance of 70 s/m and albedo of 0.23" by Allen et al. (1998). In the presence of snow in a non-forested area, the maximum albedo value was 0.80 (Morten, 2007). The actual evapotranspiration (ET_t) can be calculated by reducing the PET according to soil moisture i.e. available soil water for plants (Feddes et al., 1978), and according to the crop coefficient. Allen et al., (1998) suggested that crop coefficient decreases to the end-stage and so crop coefficient was calibrated in this study. The hourly potential evapotranspiration was computed according to the Penman-Monteith equation (Allen et al. 1998).

$$ET_o = \frac{0.408 \triangle (R_n - G) + \gamma \frac{37}{T_{hr} + 273} u_2 (e^o(T_{hr}) - e_a)}{\triangle + \gamma (1 + 0.34 u_2)} \tag{5}$$

where ET_0 (mm/h) is the reference evapotranspiration, R (MJ/m^2/h^1) is the net radiation at the grass surface, G (MJ /m^2 /h^1) is the soil heat flux density, T_{hr} (°C) is the hourly temperature, $\triangle$ (kPa /°C) is the saturation slope vapor pressure curve at T_{hr}, γ (kPa /°C) is the psychometric constant, e^o (kPa) is the saturation vapor pressure at air temperature T_{hr}, e_a (kPa) is the average hourly actual vapor pressure, and u_2 (m/s) is the average hourly wind speed at 2 meter.

Magid et al. (1994) noted that the presence of vegetation would reduce PET from potential evapotranspiration. Turunen et al. (2013) reported the value of 0.7 as the crop coefficient. The actual potential evapotranspiration was calculated using Equation (6). A value of 0.62 was used for crop coefficient and assumed constant throughout the study period.

$$ET_t = C_f \, K_{ref} ET_o \tag{6}$$

where ET_t (mm/h) is the actual evapotranspiration, C_f (-) is the correction factor based on soil moisture (Feddes et al., 1978) and K_{ref} (-) is the crop coefficient.

3.3.2. Computation of soil parameters

The Drainmod-based model required determination of soil parameters (see Table 5 in section 3.4.1) for simulations. The parameters were measured from undisturbed soil cores, two soils samples were taken from each field subsection and each of the field section (ND, CD and CDI) Missing parameters were taken from literature. The water retention curve for the soil layer was calculated with the van Genuchten (1980) model, where the soil moisture in each layer is computed with Equation (7).

$$\Theta_i = \Theta_{res,i} + (\Theta_{sat,i} - \Theta_{res,i})/(1 + |100(\alpha)h_i|^m)^n \tag{7}$$

where, Θ_i (m^3/ m^3) is the water content in the studied soil layer, $\Theta_{res,i}$ (m^3/ m^3) is the residual water content , $\Theta_{sat,i}$ (m^3/ m^3) is the saturated water content, α (1/m) , m (-), and n (-) are the van Genuchten (1980) model parameters, h_i (m) is the pressure head, and i (-) is the soil layer.

The unsaturated hydraulic conductivity is the function of the pressure head (h) and it was calculated with Equation (8) according to Mualem (1976) and van Genucten (1980).

$$K_h = K_s \left[\frac{(1 - |100\alpha h|^{m-1}(|100\alpha h|^m)^{-n})^2}{(1 + |100\alpha h|^m)^{n/2}} \right] \tag{8}$$

Where K_s (m/h) is saturated hydraulic conductivity of soil profile, h (m) is the pressure head in soil layer i, and n and m are dimensionless parameters where n = (1-1/m).

Air volume of the soil profile used the soil moisture from soil water retention curve. Air volume of the static steady-state soil moisture distribution was used for solving the GWD. The air volume in the soil profile was calculated with Equation (9).

$$V_a = \sum_{i=1}^{imax} \left(\Theta_{sat,i} - \Theta_i\right) \triangle z_i \tag{9}$$

Where V_a (m) is the air volume, $\triangle z_i$ (m) is the thickness of the soil horizons.

The ground water flow from layers below root depth towards the root zone layers was estimated by solving the steady state form of the Richards (1931) equation (Equation 10).

In estimation of capillary upflux to the root zone, a constant pressure of -50 m was set as a boundary condition at bottom of root zone and 0 m pressure head at ground water depth (GWD).

$$0 = \frac{d}{dz}\left[K_h\left(\frac{dh}{dz} - 1\right)\right] \tag{10}$$

where K_h **(**m/h**)** is the hydraulic conductivity, *z* (m) is the distance from ground surface.

Capillary upflux (Equation 11), i.e. water flux from water table to root zone, was calculated based on the solution of Equation (10). The capillary flux (C_f) was estimated between two layers from root depth to the depth of water table.

$$C_f = -K_{h,i,i+1}\frac{h_{i+1} - h_i}{\triangle z_{i,i+1}} \tag{11}$$

3.3.3. Description of drainage equations

The Drainmod-based model calculated DD using the Hooghoudt (1940) equation. The Hooghoudt's equation assumes steady-state flow conditions and can be applied for one or multi-layered soil. The subsurface discharge for ND (q_d) and CD (q_s) were calculated with Equations (12-13), respectively. The subsurface irrigation flow (q_s) into the field is calculated with Equation (13). The main difference between Equations (12) and (13) is the implementation of weir depth, which reduces pressure head in the discharge equation. A schematic representation of the modified Hooghoudt's steady-state equations (El-Sadek, 2001) is presented in Figure 14.

$$q_d = \frac{8K_b d_e m + 4K_a m^2}{L^2} \tag{12}$$

where d_e (m) is the effective depth, K_b (m/h) is the saturated hydraulic conductivity below the drain depth, K_a (m/h) is the saturated hydraulic conductivity above the drain depth, *L* (m) is the drain spacing, *m* (m) is the depth from groundwater table to the drain depth, and h_o (m) is depth from groundwater table to the effective depth.

$$q_s = \frac{8K_b h_o m_w + 4K_a {m_w}^2}{L^2} \tag{13}$$

where q_s (m) is the sub-irrigation flow through soil, m_w (m) is the difference between water level in midway between the lateral pipes and water level above the weir depth (m).

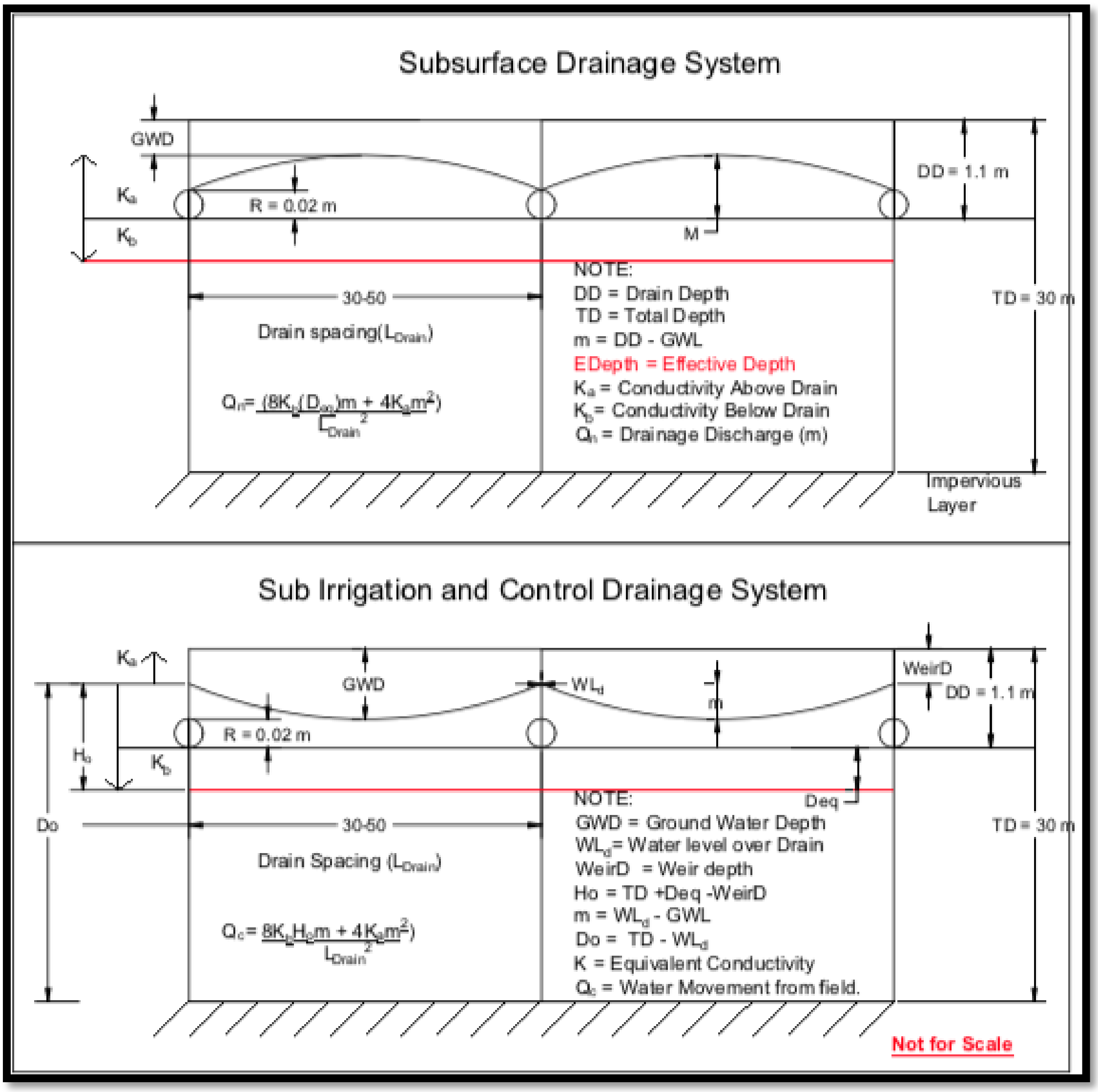

Figure 7. Schematic sketch of the modified Hooghoudt Equation (1940) for normal subsurface and controlled drainage as well as sub-irrigation according to El-Sadek et al., (2001) and the presentation of drainage system design in Söderfjärden experimental field.

Equivalent depth (d_e) below the drain pipe is computed as function of drain spacing and impermeable depth (D) below drain depth (Equation 14, El-Sadek et al., 2001).

For $0 < D/L < 0.3$

$$d_e = \frac{D}{\frac{D}{L}\left(\frac{8}{\pi} ln \frac{D}{r} - u\right) + 1} \tag{14}$$

Where u is

$$u = 3.55 - \frac{1.6D}{L} + 2\frac{D}{L^2}^2 \tag{15}$$

For $D/L > 0.3$,

$$d_e = \frac{\pi L}{8\{ln\left(\frac{L}{r}\right) - 1.15\}} \tag{16}$$

where r (m) is the inner radius of drain pipes.

The modified versions of the Hooghoudt equation requires approximation of the saturated hydraulic conductivity of soil above and below drainpipe (e.g., El-Sadek et al., 2001). Weighted average saturated hydraulic conductivity was calculated using Equations 17 and 18. The estimated saturated hydraulic conductivity of soil profile above drainpipe (K_a) was calculated from soil layers between the drain depth and the GWD above the drain. The estimated saturated hydraulic conductivity of the soil profile below the drain depth (K_b) is weighted average saturated conductivity of the soil layers between drain depth and effective impermeable depth.

$$K_a = \frac{K_{a1} z_{a1} + \ldots\ldots + K_{an} z_{an}}{z_{a1} + \cdots + z_{an}} \tag{17}$$

$$K_b = \frac{K_{b1} z_{b1} + \ldots\ldots + K_{bn} z_{bn}}{z_{b1} + \cdots + z_{bn}} \tag{18}$$

where n (-) is the layer number, K_s (m/h) is the saturated hydraulic conductivity and z (m) is the thickness of a layer.

Seepage (m/h) (in Figure 6) occurs from the soil layers below GWD and was calculated according to the Darcy's law with Equation (19).

$$S = \frac{k_{avg} \Delta h}{\Delta l} \frac{A_{cr}}{A_f} \tag{19}$$

where S is seepage outflow from the soil, k_{avg} (m/h) is the average conductivity of the soil layers below GWD, Δh (m) is the hydraulic head gradient between the soil and field boundary and field boundary for example the bottom of the main ditch, Δl (m) is the length of the soil profile where the seepage outflow occurs, A_{cr} (m^2) is the cross-section area of the seepage flow, and A_f (m^2) is the field area affected by seepage.

In the computations in the Drainmod-based model the ratio A_{cr}/A_f was set to a value of one, and the saturated hydraulic conductivity values of bottom soil layers were used as bulk calibration parameters regarding the seepage outflow as the plastic sheet was placed to control the seepage flow to the ditch from field.

3.4. Model application

3.4.1. Parameterization of the Drainmod-based model

The Drainmod-based model was applied to simulate hourly DD and GWD in the three field sections in Söderfjärden experiment field. The soil of the field sections was parameterized based on literature and soil data from the field (presented in Table 5). The simulated soil profile was divided into five different soil layers representing the soil horizons of the soil samples (Yli-Halla, 2012). The model was calibrated and validated using the measured DD and GWD from ND field section. In the calibration, GWD simulation was weighted higher than DD (minimum Drainmod-based model performance with Nash–Sutcliffe efficiency (NSE) value of 0.50 for simulating DD) due to AS soils. The impact on oxidation on the water quality of DD in AS soil is highly related with GWD and soil properties. The chosen weighting was justified because DD was measured from the whole field sections, and the model does not consider the spatial variability in the field and GWD was observed at the lowest section of the field. The modelling process for Drainmod-based model is illustrated in Figure 8.

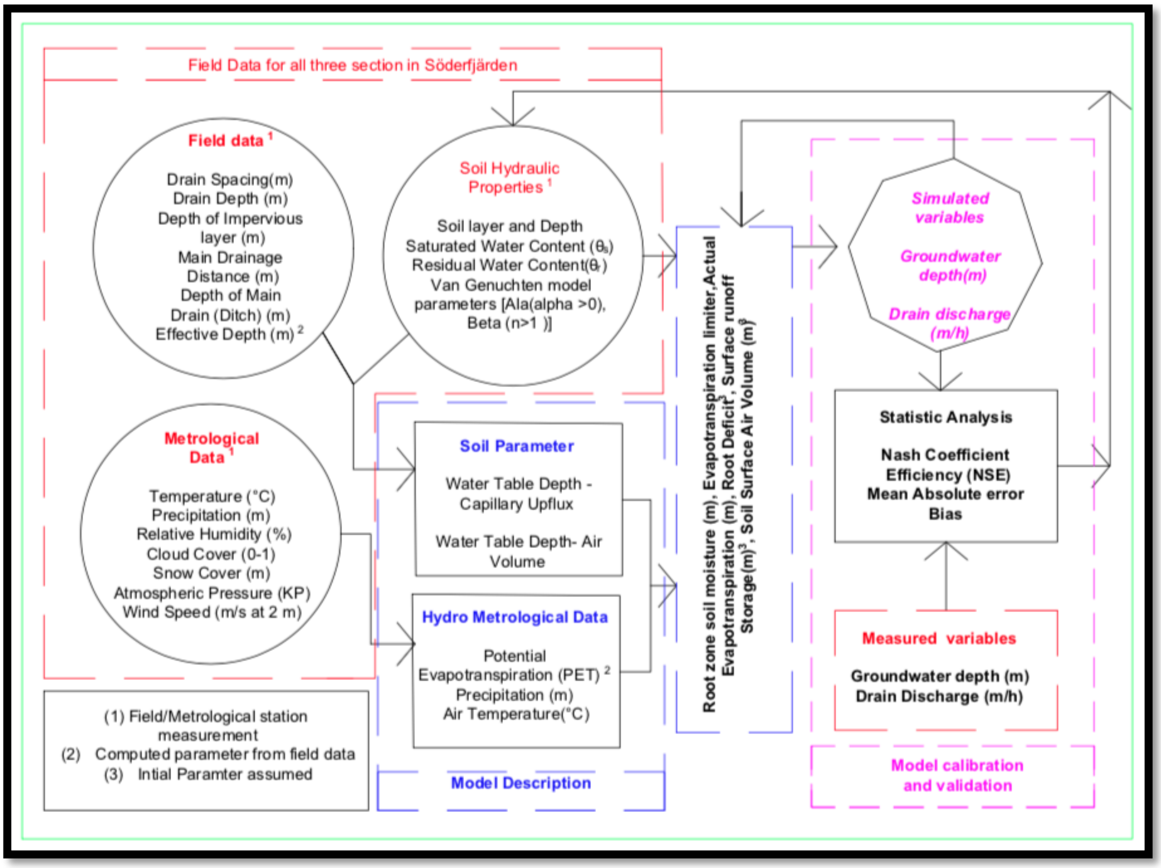

Figure 8. Modelling process and model input data. Parameters and variables inside red dash lines presents data from the study site or FMI Vaasa station. Blue dash line presents the required variables for the hydrological model, which are either measured or computed from weather station data (see Section 2.2). Pink dash line and text presents simulated model output variables. The subscript (1, 2 or 3) represents the parameters and variables that were measured (1) or computed (2).

Initial GWD for the simulation was set according to the measured GWD. The soil profile was discretized into 25 computational layers that were evenly divided across the soil profile. Rainfall or snowmelt discharge infiltrates to soil column with maximum infiltration capacity of 0.4 m/day. The snow model was calibrated for a period of 2014–2017. Hourly snow depth measurements were available from Vaasa FMI weather station. Initial values for correction factors for rainfall and snowfall were 1.05 and 1.25, respectively, according to Allerup et al. (1999) and Taskinen et al. (2016). The snow model was calibrated for a period of 2014-2017 because of availability of snow depth measurement for the calibration period. The snow model was calibrated in terms of the rainfall correction factor (1.06), the snowfall correction factor (1.25) and the degree-day snowmelt factor (k_d). A value of 0.62 was used for crop coefficient and assumed constant throughout the study period. The calibrated parameters are presented in Table 4.

Table 4. Site characteristics and model parameters for water management practices.

System design		Meteorological inputs	
Layers	5	Minimum Temperature for snowfall/rain (°C)	0
Depth of the drains (m)	1.1	Maximum temperature for snowfall/rain (°C)	+2
Spacing between drains (m)	40	Rainfall correction factor (-)	1.06
Effective radius of drain (mm)	0.25	Snowfall correction factor (-)	1.25
Drainage coefficient (-)	1	Degree-day snowmelt factor (k_d) mm/°C/day	2
Impermeable depth (m)	30	Refreezing factor (k_f) mm/°C/d	4.8
Initial water table depth (m)	*	Liquid water retention	0.2
Sub irrigation pump capacity (m/day)	0.21	Interception fraction	1
Weir depth, summer (m)	0.7	Maximum infiltration (m/d)	0.4
Weir depth, winter (m)	0.6	Snow density (kg/m^3)	320
Max discharge (mm/h) **	1.01		

(*) measured values according to different management practices
(**) calculation based on slope and diameter of collector pipe using manning equation.

The saturated hydraulic conductivity (K_s) is an important parameter for determining the rate of drain discharge (Scott et al., 2009). The measured values for saturated hydraulic conductivity were available only for 2 layers (see Table 2). Missing K_s values on each soil composition (see Table 5) were set based on literature for the 1st layer (Soil Survey office, 2014) and others were calibrated. K_s value for the 1st layer was 0.153 m/h from literature for slit loam in acidic soil (Soil survey office, 2014). K_s values from layers 2 to 5 were calibrated. Van Genuchten parameters were also calibrated for layers 2-5 but the initial values for the parameters were the measurements for 2nd and 3rd soil layers. In this study, the maximum capillary flux was 0.00021 m/h.

Table 5. Water content and van Genuchten parameter for studied soil layers.

Soil Layer	1[a]	2[b]	3[b]	4[c]	5[c]
Soil depth (cm)	0-30	30-50	50-100	100-150	150-280
$\Theta_{sat,i}$ (m^3/m^3)	0.63	0.41	0.39	0.35	0.28
$\Theta_{res,i}$ (m^3/m^3)	0.15	0.20	0.20	0.30	0.23
α (m^{-1})	0.27	0.13	0.03	0.27	0.18
m (-)	1.46	1.32	1.24	1.80	1.40
n (-)	0.32	0.24	0.19	0.44	0.29
K_s (m/h)	0.15	0.04[c]	0.02[c]	0.04[c]	0.004[c]

a = parameter based in literature, b = measured parameter and c = calibrated parameters

3.4.2. Parameterization of the HAPSU model

The simulation of field hydrology with HAPSU model was carried out in 1D. The HAPSU model was used for simulating daily hydrological variables (DD and GWD) and quality variable (pH of DD) in all fields (ND, CD and CDI). The model was not calibrated but the performance of the model was evaluated with parameterization of Drainmod-based model against field measurements (DD, GWD and pH of DD).

The soil profile was discretized into 11 soil layers (5 layers from Drainmod-based model were dived into 11 soil layers) with total depth of 3.8 m from soil surface to simulate the water balance of the field. The model used water balance approach for simulations as presented in Figure 6 (as Drainmod-based model) without seepage outflow component. The soil parameters for the model simulations were calibrated soil parameters from Drainmod-based model and partly snow model parameters (water content of the snow, minimum evaporation coefficient, temperature limit for melting and evaporation, and earth's thermal capacity) were based literature (Bärlund et al., 2005; Vehviläinen et al., 1992). The required initial chemical concentration of element in soil (pH, Al, SO_4, Fe, H_2CO_3, saturated O_2 concentration in pore water and saturated oxygen concentration in air) and chemical ions and compounds (Al^{3+}, Ca^{2+}, FeS, FeS_2, $FeOH_3$ and $AlOH_3$) for simulation of water quality parameter of DD were based on literature (Österholm et al., 2015) and are presented in Table 3.

The inputs for model were the measured average daily air temperature, and measured (uncorrected) precipitation, and five days cumulative ET_o from May till September. The rainfall and snowfall correction values were dynamic inbuilt in the model. The rainfall correction factor range (1.07- 1.15) and snowfall correction factor range (1.25-1.45). The input ET_o was not limited by crops coefficient (K_{ref}). The model used conventional subsurface Hooghoudt (1940) drainage for simulation of controlled drainage. In this study, sub-irrigation was implement by increasing the precipitation as implemented by Kosunen et al. (2012).

3.4.3. Calibration and validation of the Drainmod-based model

The Drainmod-based model simulation results were compared with automatic hourly measurements of DD and GWD for ND field. Simulated GWD was additionally compared to manual measurements. The Drainmod-based model was calibrated for the period from October 2010 to December 2014 DD with seepage routine. The model performance was validated using period of January 2015–December 2017. Figure 9 shows calibration and validation period with measured and interpolated GWD. Model calibration was done manually by changing one parameter at a time. The parameters were changed to fit the model output with the measured DD and GWD for the ND field. The performance of the model was evaluated with GWD and DD. During the model calibration the model performance was prioritized on simulating GWD, but limit was set for simulating DD with minimum NSE value of 0.50. The calibrated parameters of the ND field (Table 5) were used for validating the drainage model for the CD and CDI field. The calibrated model performance was tested by running the model for the both CD and CDI fields by changing the drainage equation sub-model in the Drainmod-based model (see Section 3.3.3). The most sensitive parameters in terms of simulation results were saturated hydraulic conductivity, rainfall correction factor, snowfall correction factor, and van Genuchten parameters for the 3rd, 4th and 5th layers.

Drain depth, drain spacing, and the radius of a drain pipe for the model application were taken from the field drainage system design (Table 4). For CD and CDI field sections, there was information about the changes in weir depth and records of the pumped water volume. The model parameterization is described in Table 4. The Drainmod-based model was able to simulate only one crop type per simulation period. The cultivated crops in Söderfjärden experimental field were barley and wheat. During the model calibration, maximum root depth of 25 cm was assumed for the growing season. The depth for potential evapotranspiration was limited to 5 m from soil surface. The soil properties were determined only for the 2nd and 3rd layer although soil parameters for this horizons were calibrated. Initial values for the calibrated parameters for the 4th and 5th horizons were set according to the 3rd layer properties. The 4th layer was potential acidic sulfate layer whereas the 5th layer was silty clay loam with high clay percentage (Table 3).

The automatically measured GWD time series were adjusted based on the manual GWD measurements. Missing automatically measured GWD time points were replaced by linearly interpolated (pink dash line in Figure 9) using the manual measurement. There was a clear difference between the manual and automatic GWD measurements after 2015 (Figure 9). The difference between the automatic and manual measurement occurred because in the manual measurements the elevation changes of the observation tube due to freezing had been taken into account, but not in the automatic measurements. To correct the automatic continuous GWD measurement, the difference between manually and automatically measured GWD was used to linearly interpolate the automatic measurements. The maximum difference between the manual and continuous measurement in the lowest subsection in CD field was recorded in October 2012 with the value of 1.4 m in CD field (Figure 9) which made it difficult to interpolate GWD. Based on continuous measurements, similar fluctuation in GWD was observed in all the fields after interpolation of continuous automatically measured GWD. After the interpolation, GWD was decreased in the lower section of each field.

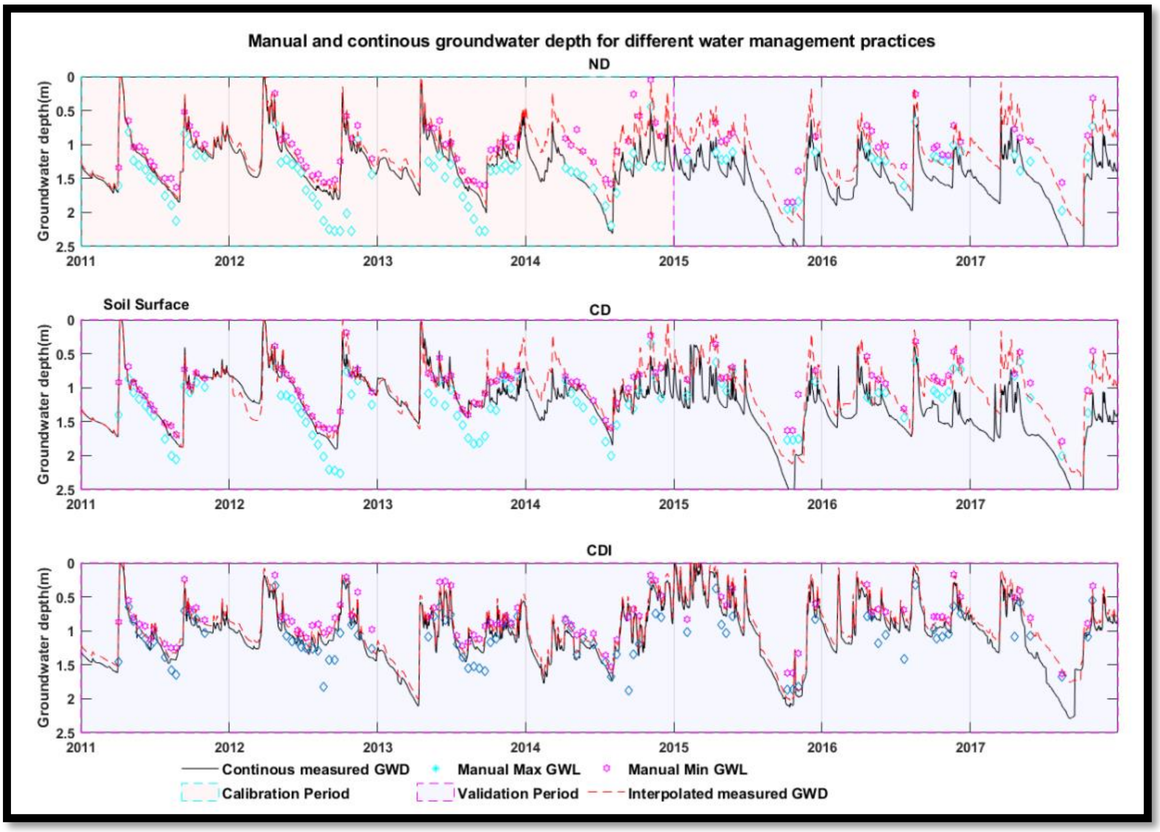

Figure 9. Manually (markers), automatically (black line) and interpolated (red dash line) measured ground water depth for normal subsurface (ND), controlled drainage (CD) and CD with sub-irrigation (CDI) practices in the lowest sub section of the field sections. The blue dash line box is calibration period. The pink dash and shaded period is the validation period. Diamond marker is GWD in the high subsection in the field whereas hexagonal marker is GWD in low subsection.

The HAPSU model was run with the Drainmod-based model parameters with the normal drainage equation (Equation 12). In HAPSU model, DD in CD and CDI field is calculated with the same equation as ND field. The performance of the Drainmod-based model was assessed with hourly interpolated measured DD and GWD against simulated DD and GWD. For comparing the HAPSU model output to the measurements, hourly measurements values were accumulated to daily values and performance was assessed comparing measured DD and GWD with simulated DD and GWD. The model parameters were only calibrated for ND field section, and the CD and CDI field sections had identical parameterization for the simulations.

3.5. Assessing model performance

Model performance was assessed by comparing the simulated hourly DD and GWD to the measurement. The fit between the simulations and measurements was quantified with Nash–Sutcliffe efficiency (NSE, Nash and Sutcliffe 1970), mean absolute error (MAE, Willmott and Matsuura, 2005) and bias (Nevitt and Hancock, 2001). The NSE was computed using Equation (20).

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(r_i - r_{s,i}\right)^2}{\sum_{i=1}^{n}(r_i - r_{mean})^2} \tag{20}$$

where r_i is the continuous measured DD or GWD time series, $r_{s,i}$ is the simulated DD or GWD, r_{mean} is the average of the measured DD or GWD time series, n (-) is the length of the time series, and i (-) is the time index.

NSE was selected for model calibration and validation since NSE is frequently used for hydrological modelling (Morrison et al., 2014). NSE coefficient ranges from negative infinite to 1. If NSE equals to 1, there is a perfect match between simulated and measured time series. Negative NSE values indicate that the mean of the measured time series describes the measurement better than the simulated time series (Nash and Sutcliffe 1970).

The mean absolute error (Equation 21) was used to assess the magnitude of the error between the measured and simulated time series.

$$MAE = \frac{\sum_{i=1}^{n}\left|\left(r_i - r_{s,i}\right)\right|}{n} \tag{21}$$

Bias (Equation 22) was used to determine if the simulated values (GWD and DD) were higher or lower than the observed values.

$$Bias = \frac{\sum_{i=1}^{n}\left(r_i - r_{s,i}\right)}{r_{(mean)}} 100 \tag{22}$$

Positive bias percentage means that the model is overestimating the results in terms of measurements and negative percentage means that the model underestimating the results.

4. Results

4.1. Model calibration and validation

Figure 10 presents interpolated automatically measured and simulated ground water depth (GWD) together with the range of the manually measured GWD from all the field sections (normal drainage (ND), controlled drainage (CD), and sub-irrigation (CDI)). The range of the manual measurements was formed by taking the minimum and maximum GWD value from the three GWD observation locations (low, middle and high) subsections of each field section (see Figure 3). The Drainmod-based model predicted the measured GWD better (NSE ranging 0.36–0.68) compared to the HAPSU model (NSE -0.33–0.60) in all the fields (NSE value are presented in Figure 10). The NSE for the calibration period was 0.68 for the Drainmod-based model, and 0.60 for the HAPSU model in the lower subsection of the ND field. The NSE values for the lower subsection of the CD and CDI fields were positive for the Drainmod-based model and negative for the HAPSU model indicating insufficient model calibration for HAPSU model and lack of implementation of seepage outflow component. The MAE and bias between simulated and measured GWD during calibration and validation period for studied field sections are presented in Table 6. Based on MAE and bias values, the performance of HAPSU is quite similar to Drainmod based model but HAPSU performed better for the CD and CDI field.

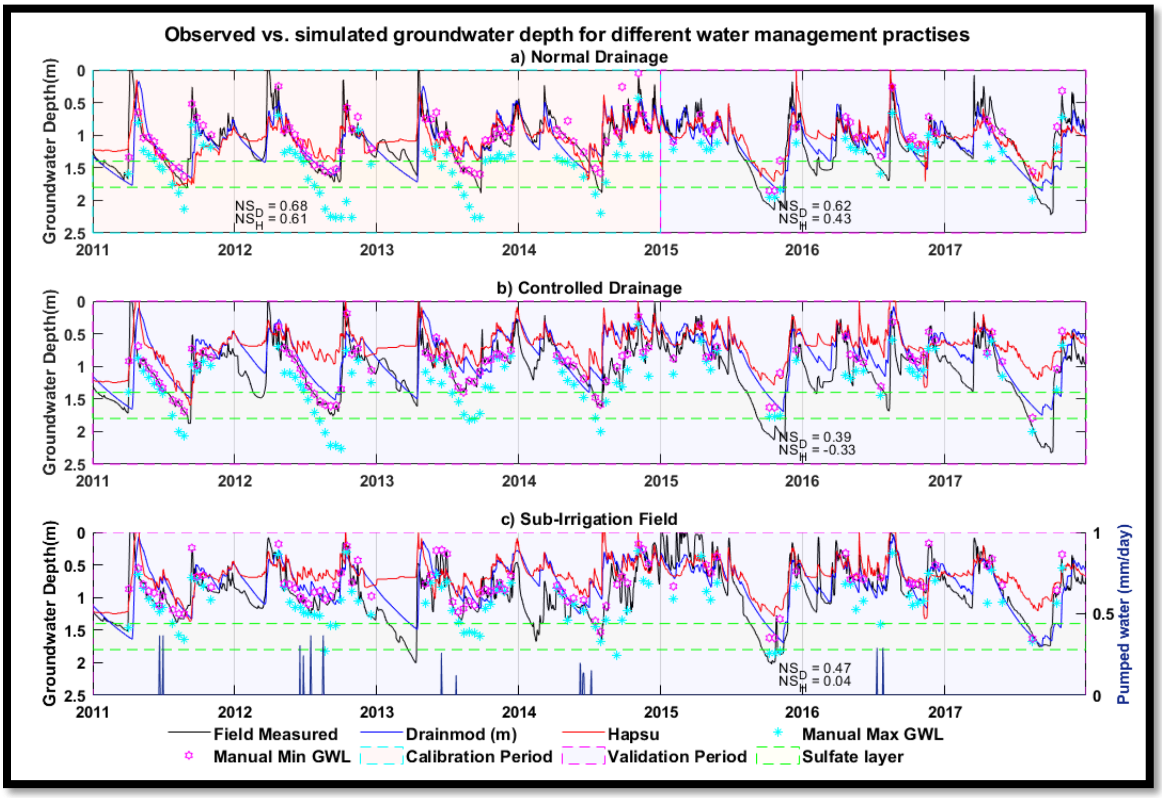

Figure 10. Automatically measured groundwater depth time series (black line) compared to simulated Drainmod-based (blue line) and HAPSU (red) GWD from Jan 2011 to Dec 2017 for the lower sections of a) ND, b) CD, and c) CDI fields. Soil surface is the depth of 0m in each field.

Based on manual and continuous GWD measurement (Figure 10), the impact of CD was visible in maintaining GWD the lower of CD and CDI fields than in ND field. The impact of sub-irrigation in CDI field was clearly visible with decreasing GWD when water was pumped into the soil profile for example in summer 2011 and 2012 (Figure 9 and Figure 10). The measurements and model outputs showed that the GWD dropped to critical layer (1.4 m) during winter and summer periods in ND field, while in the CD and CDI sections the GWD dropped below critical depth of 1.4 m only during the summer periods. In general, GWD was lowest in the CDI field than in the CD and ND fields (Figure 10). The deep GWD below the drain depth (1.1 m) was measured during the winter period when there was no evapotranspiration, which could be because of the seepage outflow from the field. After implementing the seepage outflow component in the Drainmod-based model, the model simulated GWD below drain depth during winter months (Figure A4 in Appendix A).

The simulated GWD for the low section of ND field showed that the Drainmod-based model underestimated the GWD during summer periods (MAE was in range of 0.19-0.15 mm/d) and also underestimated during winter periods (MAE was in range of 0.10- 0.21 mm/d) (Figure A2-A3 in Appendix A). The Drainmod-based model had higher NSE values (0.83 and 0.59) during dry summers 2015 and 2017 but during wet summers NSE was 0.28 and 0.15 for 2014 and 2016, respectively. The model behavior was better during cold (NSE 0.14–0.66) than mild (NSE 0.23–0.53) winters. The results were similar for the CD and CDI fields. The NSE values were lowest for summer periods 2014 and 2016 for all the field sections. In general, Drainmod based model performed better for dry summers and cold winters compared to wet summer and mild winter.

The HAPSU model gave average NSE values of 0.40 and 0.47 during the summer and winter periods respectively, in terms of simulated GWD in the ND field, respectively. On average HAPSU performed better for ND field, in terms of NSE values, during winter periods compared to the Drainmod-based model. Due to lack of seepage and model calibration, the HAPSU model performance was less satisfactory than Drainmod-based model. The NSE values for CD and CDI were below zero. The average MAE between the measured and simulated GWD was 0.475 and 0.302 mm/d for summer and winter periods, respectively. The higher bias percentage in Table 6 showed that the HAPSU model was underestimating the GWD.

Figure 11 shows model performance for calibration and validation period with both models based on DD. The Drainmod-based model underestimated daily drain discharge (DD) for all the fields (ND, CD, and CDI) while the HAPSU model overestimated daily DD. In the ND field, the Drainmod-based model underestimated DD by 32.1% whereas HAPSU model overestimated DD by 22.5%. The Drainmod-based model underestimated DD in ND, CD, and CDI especially in the beginning of the validation period (Jan 2015–Dec 2017). The lowest NSE value (0.37) for DD from the CD field was observed with the Drainmod-based model.

Table 6. The mean absolute error (MAE) and bias between observed and simulated GWD for calibration and validation periods for three water management practices (normal drainage (ND), controlled drainage (CD) and subsurface irrigation (CDI)).

	Drainmod-based Model		HAPSU Model	
	MAE [mm/d]	Bias [%]	MAE [mm/d]	Bias [%]
Calibration Period (ND) (1.10.2010- 31.12.2014)	0.15	-0.88	0.20	-1.70
Validation Period (ND) 1.1.2015- 21.12.2017	0.18	-5.34	0.25	-10.18
Validation Period (CD) 10.10.2010 -31.12.2017	0.27	-21.46	0.28	-20.61
Validation Period (CDI) 10.10.2010 -31.12.2017	0.25	-13.92	0.16	0.01

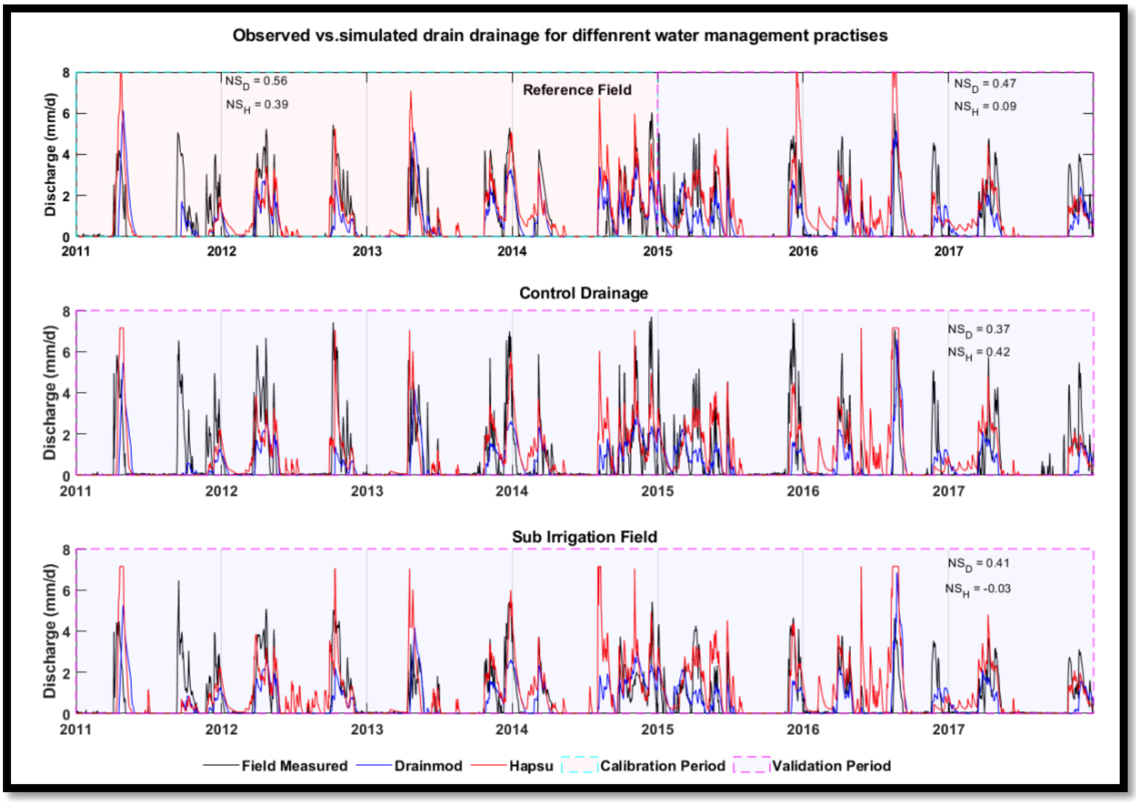

Figure 11. Observed vs simulated hourly subsurface drain discharge from Jan 2011 to Dec 2017 for ND, CD and CDI using Drainmod based (blue line) and HAPSU model (red line). NS_D and NS_H indicates NSE value for Drainmod based model and HAPSU model respectively.

During the validation period (2015–2017), the model performance decreased compared to the calibration period (2011–2014) for both models. HAPSU model overestimated DD by 8.7%, 1.5%, and 29.9% while the Drainmod-based model underestimated the measured DD by 21.7%, 39.8%, and 23.3% for ND, CD, and CDI, respectively, during the calibration period. Comparing DD during the validation period for all field sections HAPSU model overestimated the total DD by 41.6%, 25.7%, 56.6%, and Drainmod-based model underestimate by 24.7%, 40%, 24.0%. For overall study period, the model estimation of DD is presented in Table 7 indicating that HAPSU model overestimated DD whereas Drainmod-based model underestimated DD. The NSE values for the CD and CDI fields in terms of DD simulated by the Drainmod-based model were in range of 0.30 – 0.50. The corresponding NSE values for the HAPSU model were -0.03 – 0.42. The tendency of the DD event estimation was the same for both models although MAE was higher for HAPSU model because HAPSU model overestimated DD. Simulations of the Drainmod-based model produced MAE values in a range between 0.44 – 0.56 mm/day whereas the HAPSU model produced MAE value higher than 0.60 mm/d for all fields. The bias of the Drainmod-based model was always the negative indicating underestimation of DD but with HAPSU model, the bias percentage values were always positive (Bias 17.04% - 50.63%). Overall, the assessment of model performance showed that the Drainmod-based model performed better than the HAPSU model in terms of NSE values and MAE values. The Drainmod-based model predicted the DD event in all the fields more accurately compared to HAPSU.

Table 7. Water balance error in cumulative drain discharge (mm) in ND, CD and CDI for the 7-year study period (2011–2017). The percent in the parenthesis is calculated from excess volume of drain discharge (simulated DD – measured DD) with measured cumulated drain discharge. Negative percentage indicates the simulation underestimated the drain discharge and positive percentage means that the model overestimated the drain discharge.

Field Section	Drainmod-based model (mm)	HAPSU model (mm)
Normal drainage (ND)	457.58 (-22.9%)	448.65 (+22.54%)
CD (CD)	805.44 (-39.47%)	202.15 (+9.8%)
Sub Irrigation (CDI)	401.83 (-23.56)	695.43 (+40.79%)

4.2. Seasonality of drainage system performance

To investigate seasonal drainage system performance of both models, the years in the study period were divided into growing season (May-Oct) and dormant periods (Nov–April). In Finland, snowmelt typically occurs between mid-March and end of April. Figure 12 shows that the Drainmod-based model was mainly underestimating cumulative DD for all water management practices (ND, CD, and CDI) except in growing season period 2016. During May to October 2016, the measured GWD was higher than the simulated GWD (Figure 10) possibly due to the wet summer. The model underestimation could be explained by the fact that the Drainmod-based model was calibrated using mainly GWD. The underestimation of GWD increases the volume of DD after the rainfall in the model. Cumulative seasonal measured and simulated DD in ND, CD and CDI fields (Figure 12) showed more variation within summers than winters. In summers 2014 and 2016, there was measured DD but there was no measured DD in summers 2015 and 2017 due to dry summer. Based on the low precipitation intensity, DD was not observed with field sections.

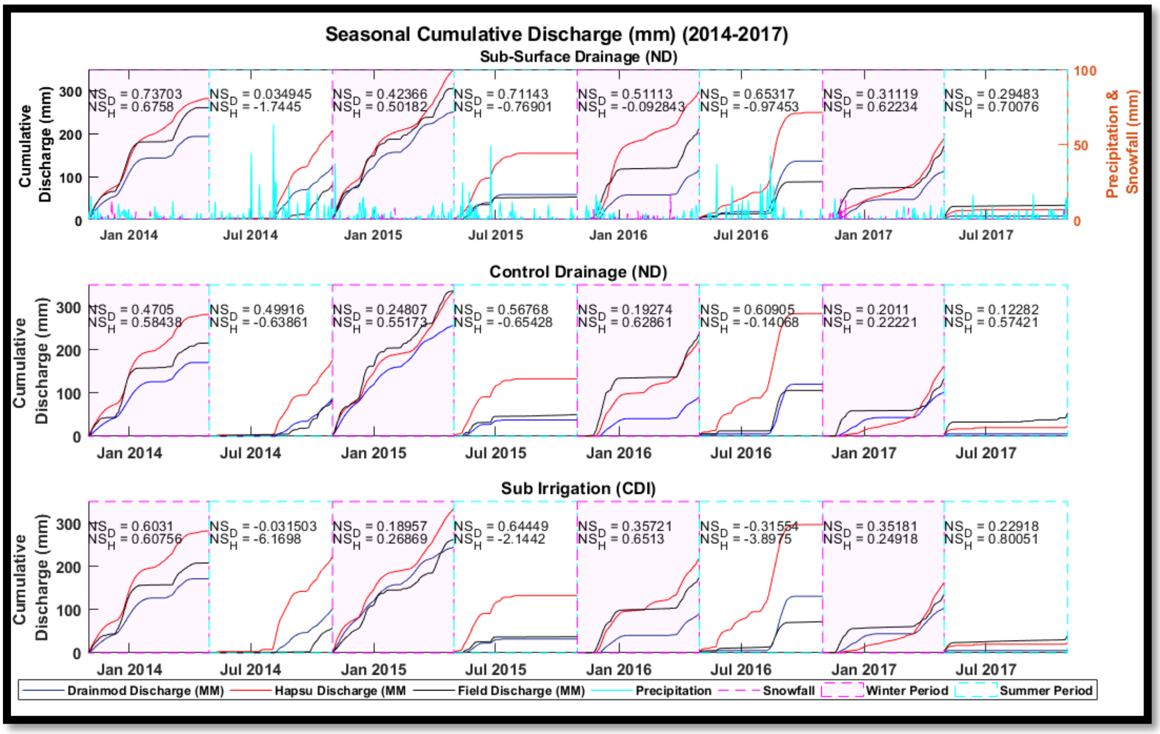

Figure 12. Observed vs simulated drain discharge (DD) from ND, CD and CDI for study period (Nov 2013- Dec 2017)

The Drainmod-based model underestimated DD for ND and CD fields during snowmelt (mid-March–end of April). During the snowmelt period there was possibly flooding in the field and the water level in the main ditch would result in less seepage from the field to the ditch as there would be a smaller hydraulic gradient between the field and ditch. The negative reading from the continuous DD measurement indicates water passing from the collector pipe to control well and water level to close to the soil surface. Figure 13 shows that the total simulated outflow with the Drainmod-based model (DD + seepage) was roughly the measured DD during the spring snowmelt period. The yearly simulated outflow (DD + seepage) was clearly higher than the measured DD. The same phenomenon was observed in the ND and CD field after the sum of the drainage and seepage, the mass error range during the snowmelt period between -7 to 7.6 %. The negative percentage could be due to the low water level in the main ditch and increased seepage groundwater outflow from the field in addition to DD.

Figure 13 compares the annual and spring time (mid-March - April) cumulative values of Drainmod-based simulated DD and seepage to the measured DD in ND and CD field. Calibration and validation of the Drainmod-based model (Section 4.1) showed that simulated annual DD was underestimated every year (2011-2017). Figure 14 shows that simulated annual DD was 20-40% smaller than the measured one. For spring period, the model underestimated DD by 7.5-40%. In the Drainmod-based model the seepage was not restricted by the water level in the main ditch.

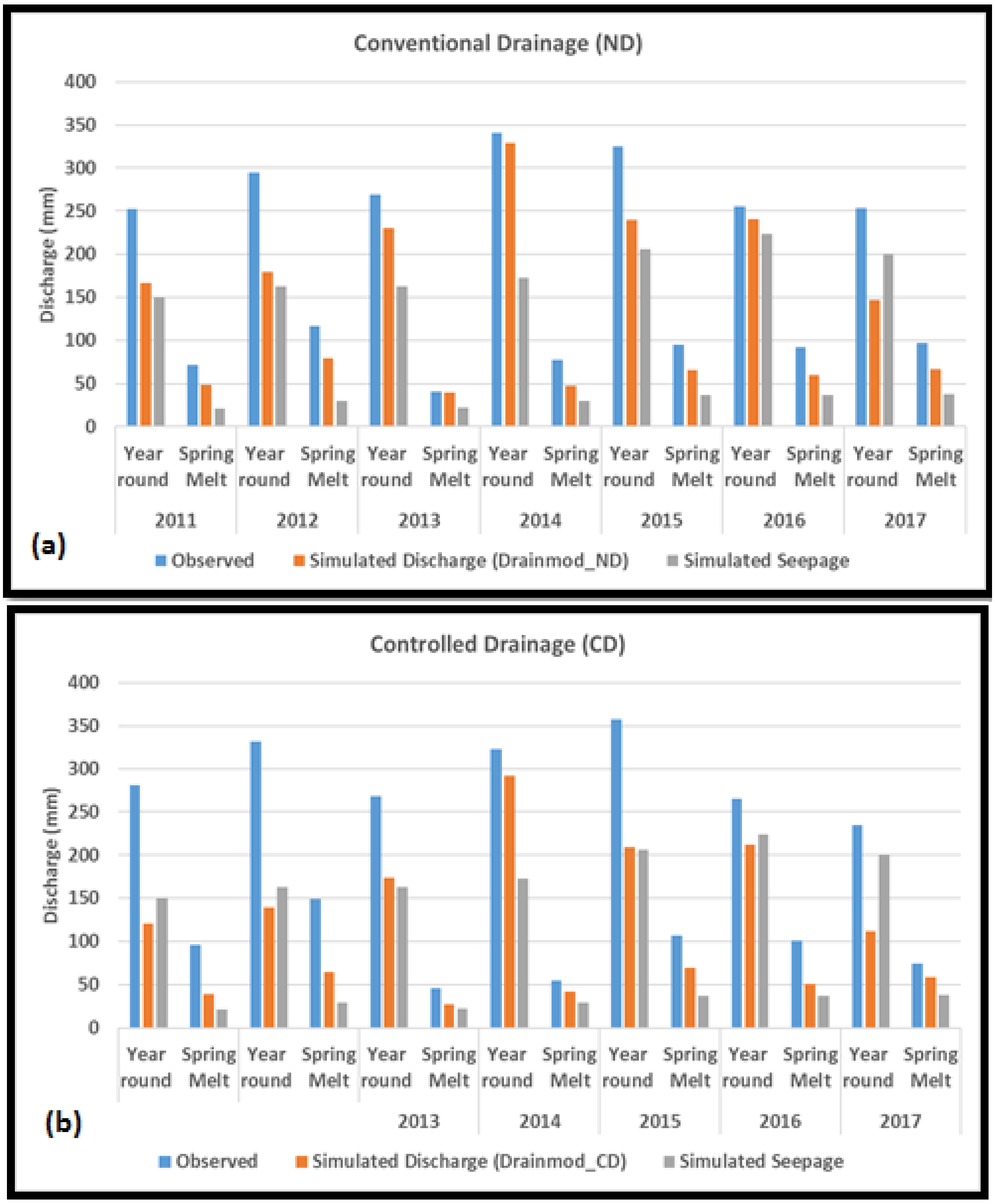

Figure 13. Annual and springtime (March to April) simulated drain discharge and seepage compared to the measured drain discharge (DD). (a) Normal drainage (ND), (b) Control drainage (CD) field.

4.3. Water balance study

In all field sections, subsurface drainage and evapotranspiration were the primary outflow components whereas surface runoff was assumed quite low due to the flat topography of the field and high infiltration capacity of the soil. The overall water balance (Figure 14 a) of the normal drainage (ND) field section was calculated with measured precipitation, measured DD, simulated actual potential evapotranspiration (ET_t) and simulated surface runoff after model calibration. To quantify the impact of control structure (used in CD and CDI field) on water balance, simulated DD, simulated seepage (groundwater outflow) and simulated actual evapotranspiration (ET_t) for each field were considered.

The Drainmod-based model underestimated the cumulative simulated DD in ND field (Figure 14). Corrected total precipitation was 4764 mm during the study period (1.10.2010 – 31.12.2017). The simulated ET_t, measured DD and simulated DD accounted for 39.48%, 43.37% and 32.7% of precipitation, respectively. The missing part of the water balance (blue area in Figure 14) between the measured water balance components and simulated ET_t over the entire study period was 17.15% of total precipitation. Simulated surface runoff was <0.5% during the study period. The missing part of the water balance refers to the unknown water balance components (soil water storage change and additional water outflow pathways). It is seen from Figure 14 that the missing part of the water balance increases after the year 2015.

To study the impact of dredging practice, the depth of the main ditch was increased to 2.7 m from 2.2 m in Drainmod-based model. The impact of dredging on water balance components were compared between periods of 1.6.2012–31.12.2014 and 1.6.2015–31.12.2017. Both study periods (before and after dredging) had the same length for the comparison. The missing part of the water balance increased from 19.03% to 22.01% after dredging (Figure 14 b-c). The increase in the missing part of the water balance was caused by decreased DD after dredging (Table 8). After dredging, the measured DD was reduced 4% for the same study period. The dredging did not have the visible impact on simulated evapotranspiration. The percentage of evapotranspiration loss was constant before and after dredging. After dredging (Figure 12 c) the percentage of simulated DD was 27.5% and before it was 33.2%. Although the model was underestimating the DD, the influence of dredging practice on DD was similar between the simulations and measurements.

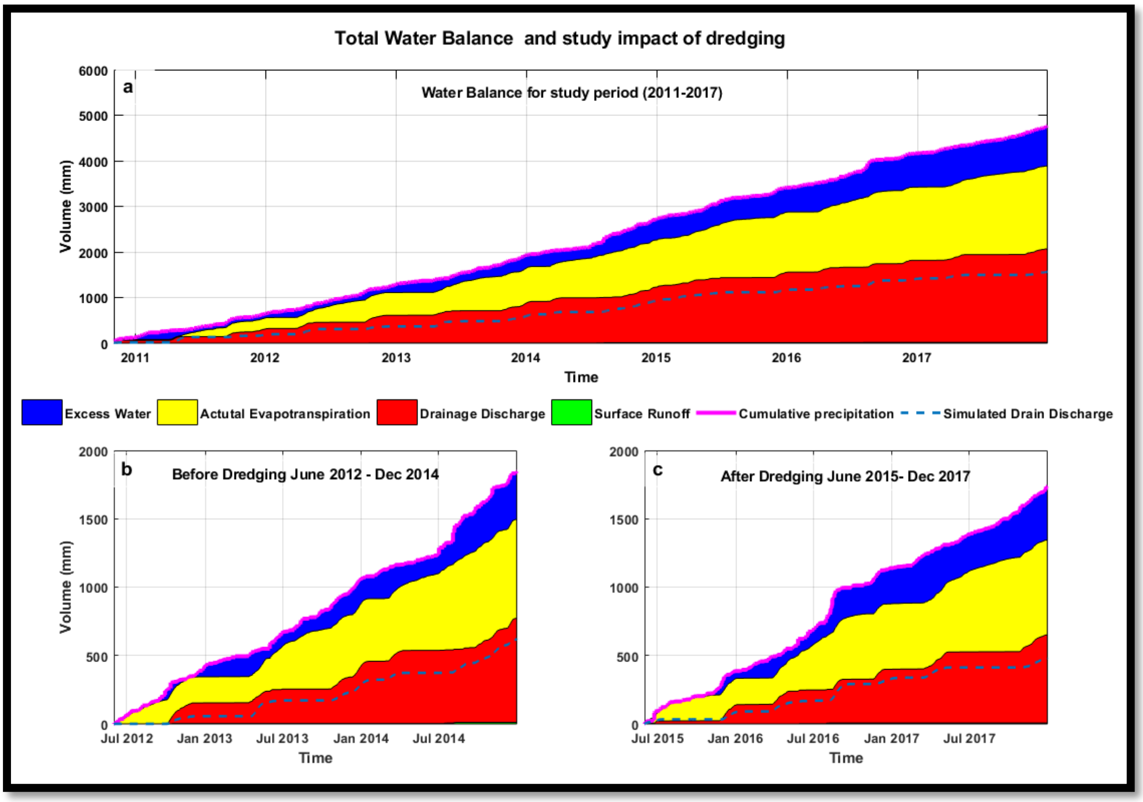

Figure 14. The water balance components of the normal drainage field section. (a) The measured cumulative precipitation (mm), measured drain discharge (mm), simulated drain discharge and simulated evapotranspiration for a seven-year-period. Blue area presents the missing part of the water balance and blue dash line indicates simulated drain discharge based on Drainmod-based model. Water balance (b) before and (c) after dredging of the main ditch in May 2015.

Change in soil water storage over the whole simulation period was estimated using the measured groundwater depth (GWD) at the beginning and end of the periods (Figure 10). GWD changed from 0.91 m (2011) to 0.82 m (2017) in the lowest field subsection, meaning that the soil water storage slightly increased in the field. In both scenarios before and after dredging, water storage in the soil profile was very small compared to the other water balance components. The difference in GWD was around 122 mm for the entire study period (2011–2017) and the missing part of the water balance was 876 mm (17.15% of total precipitation). The storage change based on GWD would be around 2.5% of total precipitation. So, the soil storage change would not explain the missing part of the water volume in water balance study. The controlled drainage (CD) field behaved similarly in terms of water balance compared to the ND field. The missing part of the water balance for CD field was in the same order of magnitude with 17.3% of total precipitation for the entire study period (2011–2017).

Table 8. The percentage of water balance output components of the ND field for the study period (7 years) and for the periods before and after dredging of the main ditch.

Study period	Evapotranspiration (%)	Measured Drain Discharge (%)	Simulated Drain Discharge (%)	Water Balance error (%)
Study period (1.10.2010 - 1.12.2017)	39.14	43.37	32.72	17.15
Before dredging (1.06.2012 - 1.12.2014)	39.14	41.82	33.64	19.03
After Dredging (1.06.2015 - 1.12.2017)	39.4	37.42	27.57	22.62

The missing percentage of the water balance in Table 8 refers to a presence of additional water outflow, and therefore, the activation of seepage component in the Drainmod-based model simulations was assumed reasonable. Because of the similar percentage of water balance error in ND and CD field sections, seepage behavior was assumed similar in all field sections.

The water balance in ND, CD and CDI fields showed differences between the water inputs and outputs. The main water balance differences between the models (Drainmod-based and HAPSU) were in evapotranspiration, DD and seepage (Figure 15). The Drainmod-based water balance showed that seepage was 27–29% of total water input. The DD and ET_t of the Drainmod-based model were 29–33.3% and 38.4–40% of total precipitation, respectively. Figure 15 shows that Drainmod-based model simulated DD was 4.4% smaller in CD field than in ND field. The simulated DD increased in the CDI field due to the water pumping.

Figure 15 shows that evapotranspiration was the biggest water balance component based on HAPSU and Drainmod-based model. HAPSU model simulated evapotranspiration over 53% of total precipitation from each field. On average over 355 mm of water was lost annually due to evapotranspiration. Compared to results of Drainmod-based model simulation the higher evapotranspiration by HAPSU was caused by 1) lack of crop coefficient in the calculation of evapotranspiration, and 2) evaporation directly from snow cover. For each field, DD was the second largest water balance component with over 35% of the total precipitation. Surface runoff by HAPSU model was 8.4–10% of precipitation. Simulated surface runoff was smallest in ND (420 mm) and the largest in the CD and CDI (535 mm). The higher surface runoff was caused because of GWD closer to the soil surface in CD field than in ND field. HAPSU model simulation caused higher water balance error compared to Drainmod-based simulation. The missing part of the water balance (in measurements) can be explained with the seepage.

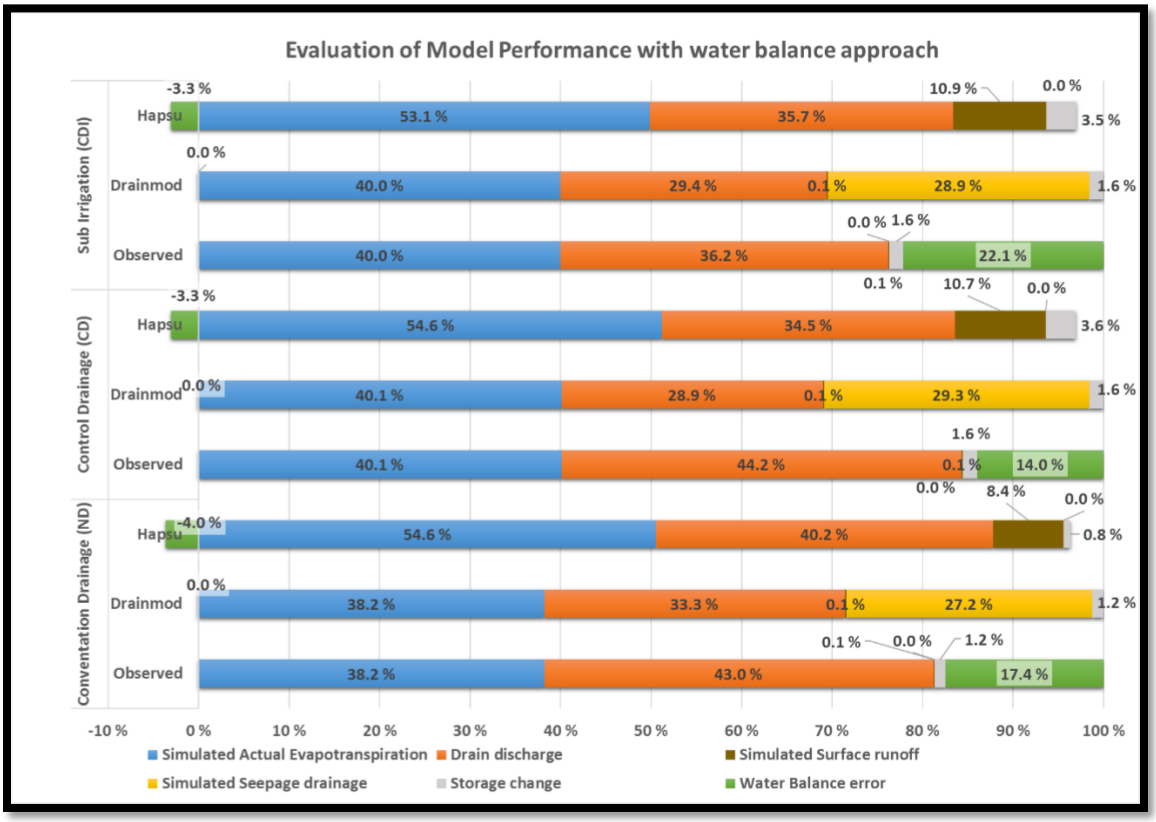

Figure 15. The measured and simulated water balance for ND, CD and CDI from 2020-2017. The percentages are relative to the water input. Precipitation was the input (4764 mm) for ND and CD, and the sum of precipitation and pumped water (141 mm) for CDI. The negative percentage means excess water outflow from the system.

The seven year mean monthly Drainmod-based DD, seepage, ET_t, and precipitation are presented for the ND field in Figure 16. During the snowmelt period (March to April), 26.2% of annual precipitation was water input to the soil column based on snow model. Other months the average infiltration amount was 7.3% of annual precipitation. In the Drainmod-based model simulation, seepage was 27.5 % of annual precipitation. Most of the annual ET_t (74.35%) occurred between May and August. Based on Drainmod-based simulation, monthly seepage from ND field was between 13 to 17 mm.

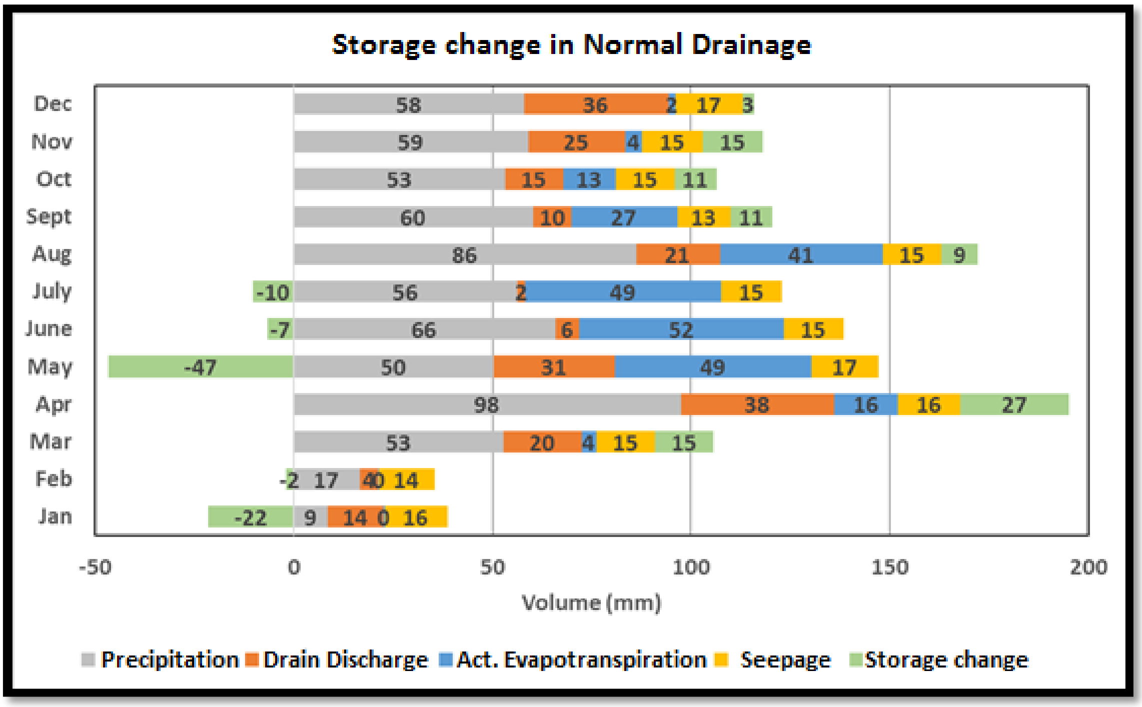

Figure 16. Monthly water storage change in normal drainage (ND). Negative soil water storage indicates that precipitation is smaller than water output components (evapotranspiration, drain discharge and seepage), i.e. water volume is lost from the soil profile. Precipitation volume takes into account the snow melting, water input is calculated as share of total snow melt based on snow model.

The monthly water balance for the ND field (Figure 16) indicates the highest storage change in May because of high water outflow from soil profile via ET_t, and DD. During May, water storage change was -47 mm in the soil profile and caused deeper GWD. The annual soil water storage change is positive (+3 mm). During January and February, infiltrating water volume was smaller than water outflow (seepage + DD) and soil water storage change was negative. The other period for the negative soil water storage change was in May–July period indicating GWD dropping period. The positive soil water storage change in August–December period (+49 mm) balanced only part of the soil water withdrawal in May–July (-64 mm).

Monthly water balance for CD field (not shown) was like water balance for the ND field (Figure 16). The impact of control structure on water balance was not strong when compared to ND on monthly bases. The monthly variation was observed for the CD field due to the controlled structure, but the overall storage change was similar in all field sections. Based on Drainmod-model simulation in CD field, annual ET_t increase by 19 mm (1.05% of total ET_t) compared to ND field.

4.4. Impact of water management practices on groundwater depth

Cumulative probability distributions of measured and Drainmod-based simulated GWD for the ND, CD, and CDI are presented in Figure 17. According to the Drainmod-based model results, the impacts of CD and CDI on GWD were greater with simulations than seen from the measurement probabilities. Approximately 23–24% of the time both measured and simulated GWD increased to the critical layer (1.4 m) for ND field. The measured GWD in the ND section was below 1.1m for 50% of the study period. The bigger difference was observed in CD and CDI performance, showing measured GWD was less than 0.99 m (CD) and 0.92 m (CDI) for 50% of the study period, whereas simulated GWD was less than 0.78 m (CD) and 0.74 m (CDI) for 50% of the study period. Similar variation in measured and simulated GWD dropping to the critical level was observed in CD and CDI field. In general, the model underestimated increase of GWD to critical depth for all field sections.

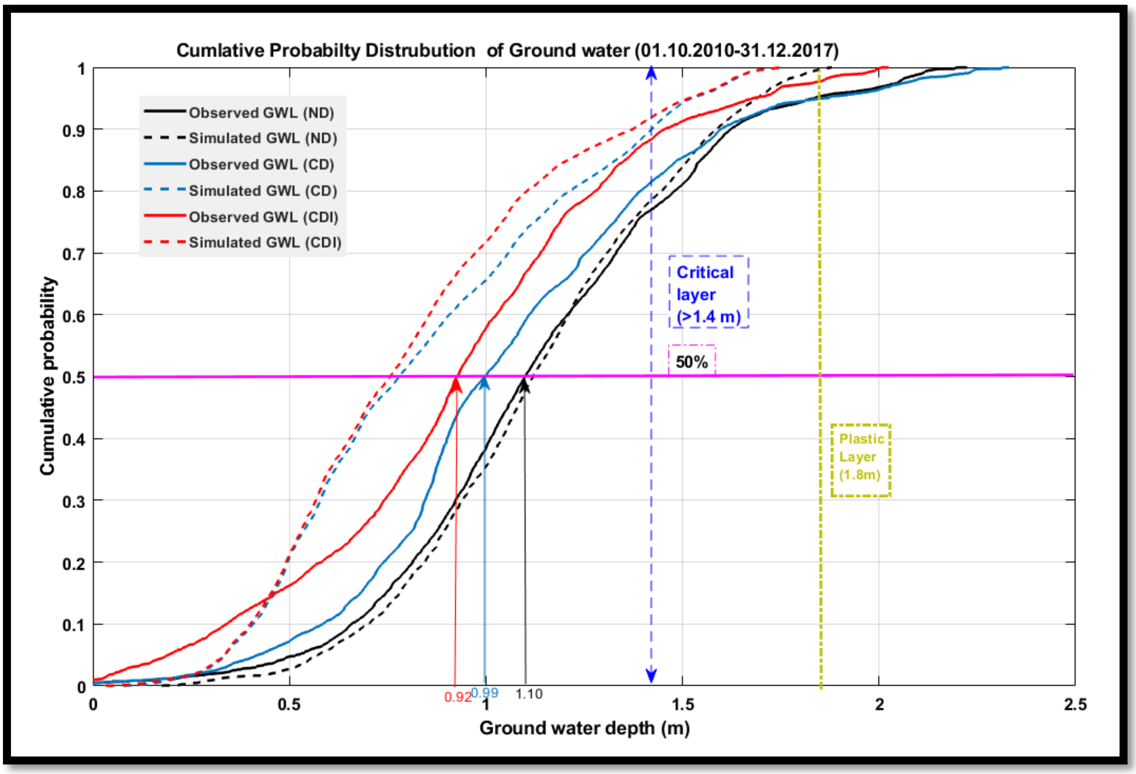

Figure 17. Cumulative probability of groundwater table depth for subsurface irrigation (CDI), CD (CD) and normal drainage (ND) field. Blue dash line indicates critical boundary layer below which there is potential acidic sulfate soil and yellow dash line represents depth of plastic sheet in the field.

In ND field the GWD dropped to critical layer 24.9 % and 19.6% of the study period for measured and simulated GWD respectively. There was more variability between the simulated and measured cumulative probability of the CD field compared to the ND field. Based on the measured and simulated GWD time series for CD, GWD dropped 20.1 % and 10.4% of time respectively, to critical layer. Only 12.3% of the study period, GWD dropped to critical layer for CDI field. The model results showed how the water management practice should affect GWD, but the similar behavior was not seen in the measurements (Figure 17). The cumulative probability distribution of the measured GWD showed CDI had a greater effect on the GWD than CD.

4.5. Water quality of drain discharge

The HAPSU model was used for simulating the water quality of DD from all field sections (ND, CD, and CDI) for a period of 2011–2014. The measured pH of DD from the ND field was lower than the pH of DD from the other fields (CD and CDI). The measured pH of DD followed the soil pH and depended on the GWD. During the snowmelt period in spring (March-April) the pH of DD was higher (around 4.0–4.2) than after summer (pH <4) when the deepest GWD was measured. The pH of DD seemed most affected by the soil properties and seasonal hydrology. During the simulated period (2011-2014), the measured pH of DD ranged between 3.8 and 4.4 and the range for the simulated pH was smaller (4.0-4.4). Figure 18 shows that the GWD dropped below acid sulfate layer in the ND section during winter, which was followed by the lowest measured pH (3.8).

The measured pH of DD from the CD and CDI field sections behaved similarly with pH from the ND field (Figure 18). In the CD and CDI field sections, GWD was closer to the soil surface than the ND which probably caused higher pH value of DD in the CD and CDI field sections than the ND field sections. These results indicate that the GWD affected the water quality. Higher GWD resulted in slightly lower pH in DD as the soil pH was lower in the deeper soil layers (see Table 3)

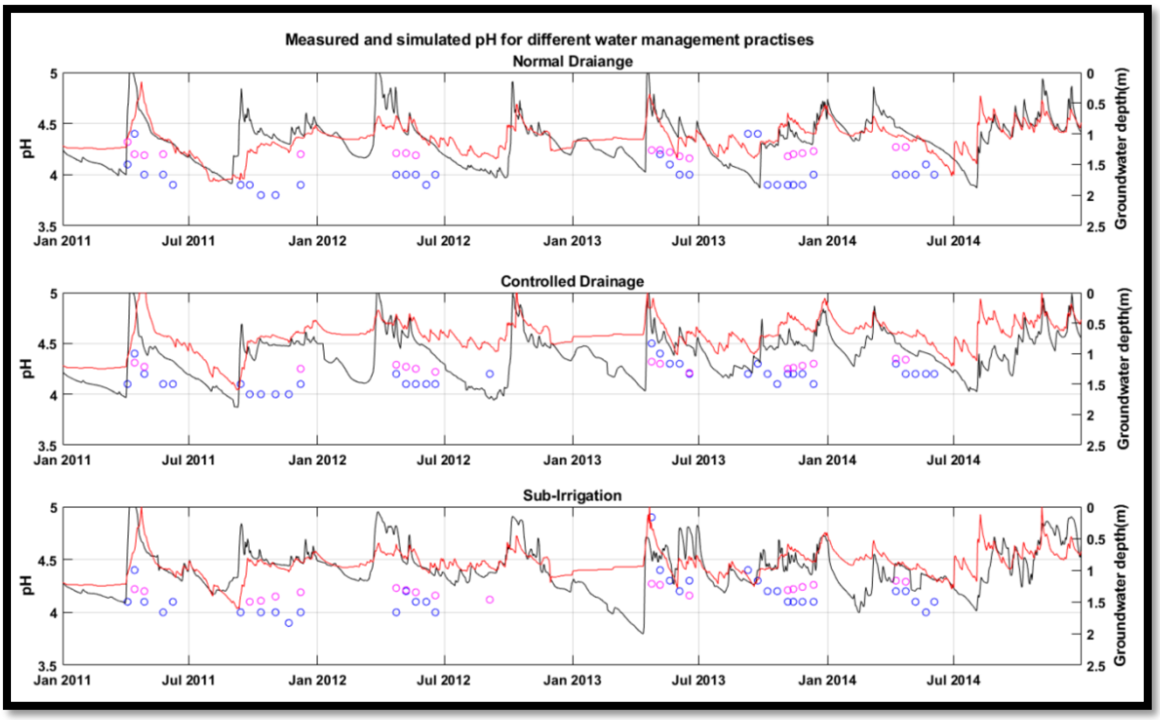

Figure 18. Measured (blue mark) and simulated (pink mark) pH of drain discharge. Continuous black and dash red lines indicate measured and simulated GWD for normal drainage, controlled drainage and sub irrigation field sections.

The simulated pH values of DD by ranged between 4.2 – 4.3 while measured pH ranged 3.8–4.4 for ND field sections. Simulated pH for CD and CDI fields had similar range but the measured pH was above 4 throughout the study period. The difference between the simulated and measured pH was approximately 0.1–0.3 pH units. Water management practice seemed to have a higher effect on the pH of DD based on the measurements. The pH varied more between the fields based on the measurement than based on the simulations. Although the simulated pH varied less than the measured pH, the simulated pH of DD based on water management practice was similar (like lowest for the ND and similar for the CD and CDI fields).

4.6. Control structure scenarios

The Drainmod-based model was used to study the theoretical impact of the weir depth in the control well on GWD and DD. The slope of the field should impact the effectiveness of weir depth. The maximum elevation difference between control wells in lower field subsection was around 0.30 m and 0.25 m for CD and CDI fields sections respectively. Scenarios were based on elevation difference between the center of field section and control well and the elevation difference was subtracted to generate similar effective weir depth. After the correction of the weir depth in Drainmod-based model, the performance of the model for simulating GWD and drain discharge is presented in Figure 19 and Table 10.

Table 9. Impact of the effective weir level on average groundwater depth and drainage discharge and model performance for simulating GWD based on Nash – Sutcliffe model efficient coefficient (NSE) based on Drainmod-based model.

Water management Practice	Scenarios for [△Weir depth (cm) from soil surface]	Average GWD from soil surface (m)	Cumulative DD (mm)	NSE for Drainmod-based model
Controlled drainage (CD)	*Measured**	1.06	2062	-
	*Normal***	0.85	1241	0.34
	+5	0.89	1280	0.47
	+12	0.93	1337	0.57
	+25	1.01	1436	0.65
Sub Irrigation (CDI)	*Measured**	0.93	1704	-
	*Normal***	0.81	1303	0.47
	+5	0.85	1346	0.53
	+12	0.89	1404	0.57
	+25	0.98	1492	0.58

* indicates field measurement with seasonal weir depth (summer (-60cm) and winter (-70cm) and ** indicates practiced weir depth in lower sub section of each field with flat topography based on simulation

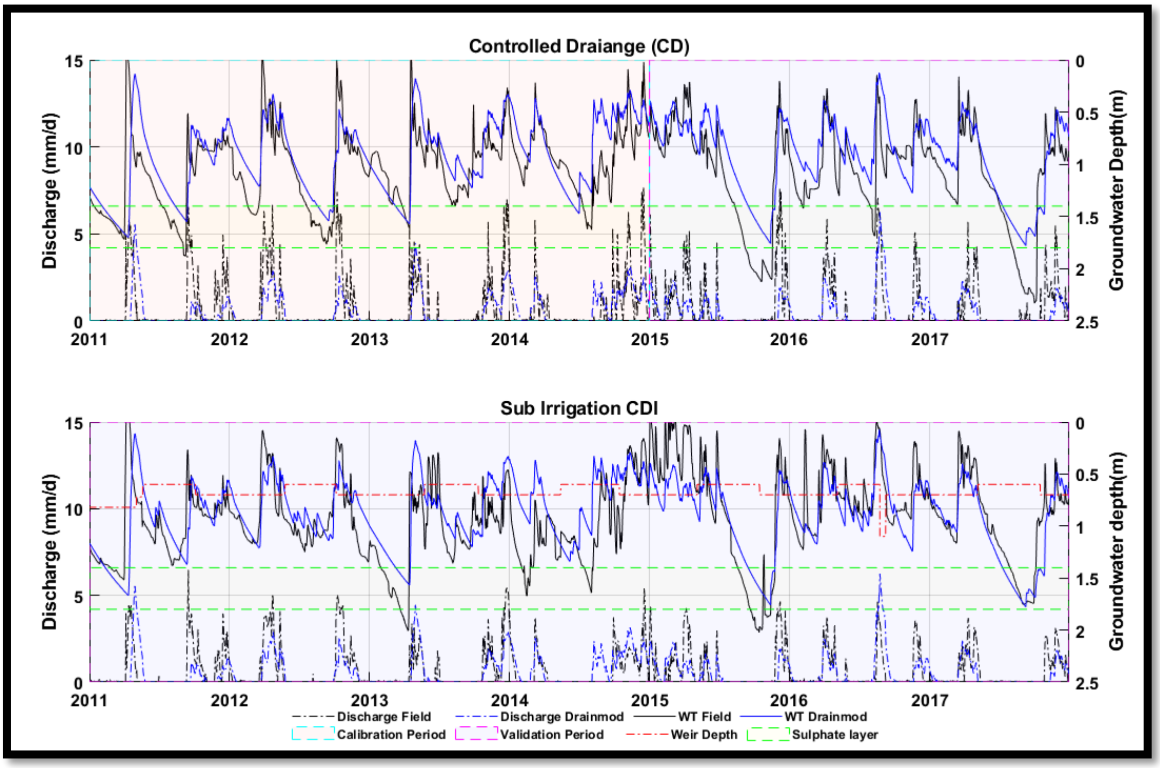

Figure 19. Impact of change of effective weir depth at center of the field section (+0.12m) for CD and CDI field. Continuous light blue line indicates weir depth change practiced in the model.

Based on NSE values in Table 9, the performance of Drainmod-based model improved for simulating GWD with increased weir depth. The Drainmod-based model was still underestimating DD although the average GWD increased with lowering weir level (Table 9). When weir level was dropped by 0.12 m, the probability of GWD reaching to critical layer increased to 17% and 16.4% of the total study period for CD and CDI field respectively. Table 9 indicates how average GWD increased further away from the control well because of the effect on weir is reduced by sloping of the field. The NSE value in Table 9 indicates Drainmod-based model performance improved after decreasing weir level. Figure 19 shows how the field topography can influence the performance of control structure (weir) to maintain GWD. The effective range of control structure showed that CD might not influence GWD throughout the field. This raises a question about considering the pressure head loss of about 0.10 m during the 1D modelling.

5. Discussion

5.1. Modelling field hydrology in cold climate

The Drainmod-based model yielded NSE values for a study period of seven years in the range of 0.45–0.55 and 0.62–0.69 for hourly drain discharge (DD) and groundwater depth (GWD), respectively after including seepage outflow component in the model. Singh et al. (2006) reported that NSE above 0.5 is considered good. In past, Drainmod model has been successfully used for simulating subsurface DD in shallow GWD (e.g., Salazar et al., 2009; Singh et al., 2006). Morrison et al. (2014) used slightly modified NSE methodology for evaluating the model performance and mentioned the Drainmod underestimated peak flow. Morrison et al. (2014) simulated daily subsurface DD with Drainmod in Canada with NSE values ranging from 0.1 to 0.6. In this study, Drainmod-based model also underestimated both peak flow and DD (Figure 11). Morrison et al. (2014) noted that the model underestimated DD but the performance for simulated DD was stable throughout the study period. The Drainmod-based model underestimated DD in this study because of the seepage from the field to main ditch and model calibration for simulating GWD. Qualitatively similar behavior was observed in the Söderfjärden experimental fields and predictions could be improved if the model was calibrated based on DD instead of GWD. The prediction of DD in Söderfjärden experimental field could be improved if models would consider the spatial variability of GWD throughout the field. The simulation of field hydrology in this study was made more realistic after implementation of seepage. El-Sadek et al. (2001) compared three models and reported Drainmod has higher performance for simulating of DD although model overestimated the DD compared to manual measured DD. The MAE for our study for DD ranged from 0.40 to 0.50 mm/d with both models whereas El-Sadek et al. (2001) observed MAE value of 0.94 mm/d. The possible explanation for this behavior of Drainmod in El-Sadek et al. (2001) could be because of Thornthwaite equation (Thornthwaite, 1948) for computation of potential evapotranspiration (PET). The model overestimated DD in El- Sadek et al. (2001) because the Drainmod model was calibrated against measured DD only. In this study, Drainmod-based model was calibrated with measured DD and GWD to fit the model output with NSE value over 0.5. In many studies, the model is calibrated with single measured variable, and one reason might be that it is difficult to fit the model outputs to several variables. Many studies of Drainmod model have calibrated with measured DD (e.g., El-Sadek et al., 2001; Morrison et al., 2014; Salazar et al., 2009).

Low DD, continuous seepage and high evapotranspiration from soil profile caused GWD dropping below the drain depth (1.1 m) during the summer period in Söderfjärden experiment field sections. Evapotranspiration is the important water outflow component in the agricultural field and has been noted as the cause for deeper GWD in the summer period (May-September) in northern conditions (Turunen et al., 2013; Magid et al., 1994). In AS soils, it is as important to simulate GWD and DD because GWD determines the oxidation of sulfidic materials and the volume of acidic DD. So, model calibration based in a single variable might not be sufficient in AS soil to understand the impact of different water management practices on water quality of DD.

Studies, where Drainmod is used for simulating field hydrology in AS soils in Nordic conditions are rare. Väisänen (2014) applied Drainmod model for simulating GWD in normal drainage (ND) field in Söderfjärden experimental field but the model was not validated for DD. Calibrating the models in ND field with the seepage outflow component in this study had satisfactory performance compared with the study of Väisänen (2014). Wahba et al. (2002) used Drainmod model for studying the surface irrigation system in the semi-arid region. In Washba et al. (2002) the simulated GWD was underestimated for ND field and overestimated for CD field. Models in the current work underestimated GWD for CD field throughout the simulation period because the model did not take into account the impact of the slope of the field and its impact on control well used for pumping water in CDI field. All water flow process in the field were not considered in the modelling. There are suggestions that CD should not be used for sloping fields with the slope more than 0.5% (e.g., Evans et al., 1995; Lambert et al., 1983). Söderfjärden is flat (slope of 0.14 %) and the effectiveness of controlled structure was affected with a small slope (Figure A5 in Appendix A). The manual GWD measurement tube was close to control well and the impact of pumped water to field on GWD could not be similar because of sloping field. The GWD difference between field sections suggest that the effectiveness of control structure was not uniform throughout the field (Figure 9). In the model, water was pumped evenly throughout the field section despite the topography of the field which could possibly result in model underestimating the GWD in each field subsection. The surface runoff was not measured at the field, but there were qualitative observations about surface runoff during snowmelt and precipitation events. Water was observed to flow from one field section to another by surface runoff. So, the modelling field hydrology without considering the field topography might reduce the performance of the model.

The HAPSU model simulated field hydrology with calibrated Drainmod-based model parameterization in this study. Water quality variables of DD in AS soils were strongly related to the field hydrology and soil properties (e.g., Bärlund et al., 2005). HAPSU simulated GWD with NSE values range of 0.43–0.60 and 0.09–0.39 for DD in ND field. Bärlund et al. (2005) applied HAPSU in AS soil field 10 km and 70 km from Söderfjärden and reported NSE value around 0.16 for simulating GWD. Based on the NSE values, HAPSU performed well in Söderfjärden field even without considering seepage outflow component in ND field. HAPSU compensated for the seepage from the field by high potential evapotranspiration during the summer and evaporation directly from the snow cover during the winter period. For CD field, Bärlund et al. (2005) mentioned HAPSU model simulated GWD close to surface during the winter months. The model was not able to simulate the deep GWD during the winter and summer period without seepage outflow component. Similar behavior of HAPSU was observed in this study. Deeper GWD in the Drainmod-based model was simulated with seepage indicating the additional flow path of water to ditch which resulted in increased GWD during winter and summer period. Without the implementation of seepage routine, Drainmod-based model simulated field hydrological variables similar as a HAPSU model (Figure 4A in Appendix A).

The GWD measurements in Söderfjärden field sections (Figure 9) showed that GWD dropped to critical layer during winter (January–February), which has been reported in other studies (Bärlund et al. 2002; Österholm et al., 2015). The phenomenon is also observed in other non-AS fields like in Nummela and Gårdskulla in Finland (Häggblom 2017, Turunen, 2015). Bärlund et al. (2002) mentioned the GWD dropped during the winter period and potential risk of dropping below the drain depth or even to critical soil layer. The dropping of the GWD during winter could be with the low infiltration to the soil due to soil freezing and water stored in the snowpack. Dropped GWD during the winter periods indicates additional water flow pathway from the field possibly to the main ditch during the winter months. Based on snow model computation, snowmelt was low during the winter period and there was no additional water volume balancing decreasing storage change or groundwater outflow which deeper GWD.

Moreover, water management practice affects the GWD in the simulations, but the similar effect was not seen from the measurements with CD or sub-irrigation. The different behavior between the measured and simulated field hydrology indicates that all water flow processes in the field were not taken into account in the modelling, for example, water flow between the field sections and water level in the main ditch. Based on simulated and measured result (Figure 17) for the water management practices, the effect of water management practice is visible for maintaining GWD in the CD and CDI field.

5.2. Effect of slope and soil on groundwater depth

Deeper GWD was observed in high subsection of the field but the groundwater level with reference to impermeable layer was higher in the high subsection of each field section (see schematic drawing in Figure 5A in Appendix A). The biggest difference in measured GWD was observed (difference between maximum and minimum GWD in Figure 9) between the high and low subsection of each field. Muma et al. (2016) pointed out the deeper GWD are observed close to the main ditch and GWD gets shallower further away from the main ditch in the flat field. In the Söderfjärden experimental fields, due to the slope of the field, GWD was higher in the high sections of the fields because of slope of field and possibly horizontal water movement and groundwater level was higher in the high subsection than the low subsection of the field (Figure 5A in Appendix A). Increased GWD in high field section indicated horizontal water movement in the sloping field. As the deeper GWD was measured in the high subsection because of elevation difference, field section might cause more oxidation of sulfidic materials. Other studies with sloping fields have reported groundwater outflow is higher with sloping fields (Turunen et al., 2015). If the groundwater outflow is higher with sloping agricultural field, the quality of DD could be highly acidic with deeper GWD and model underestimating DD in 1D model is reasonable.

The field was assumed to be homogenous in the models although saturated hydraulic conductivity (K_s) of soil is spatially heterogeneous (Scott et al. 2009). The oxidation of the AS soil has great potential to alter the soil structure and hydraulic conductivity. So, it is difficult to identify the hydraulic conductivity of AS soil without studying soil across spatial and temporal scales (Dent and Pons, 1995; Virtanen et al., 2014). The Drainmod-based model did not take into account the dynamic soil structure that is reported occurring in AS soils (Dent and Pons, 1995; Virtanen et al., 2014). The heterogeneity of soil structure is included in HAPSU model, which has a shrinkage sub-model with reversible soil properties. The effect of water management practice could possibly be linked to changes in soil structure. To understand field hydrology in AS soil and understand all water flow processes in the field, taking into account the spatial variability of soil properties could be beneficial for further studies.

5.3. Drain Discharge

5.3.1. Effect of AS soil on drain discharge quality

Based on measured pH of DD from each field section, water management practices had a clear impact on water quality. Lowest pH was observed in DD from ND field and pH of DD increased with CD field. Measured pH was higher from CD field than ND field (Bärlund et al., 2005). Simulated water management practices showed similar behavior with HAPSU model although the model overestimated the pH of DD for all water management practices. Simulated pH in Bärlund et al., (2005) was also overestimated by the HAPSU model. The result from HAPSU modelling indicated the pH of DD decreased with deepening of GWD. Seasonal variation was observed from both measured and simulated pH of DD. The simulated pH of DD was the lowest during snowmelt in springs and after summers when GWD decreased to drain depth after rainfall. The seasonal variation on pH of DD was lowest after rainfall and later the variation in pH was observed in DD in the study of Toivonen (2012). In this study the model overestimated pH of DD because the simulation of pH of the DD was highly dependent on the soil properties and field hydrology. Simulating the field with homogeneous soil properties likely increased the uncertainty of simulated pH. Based on the manual GWD measurement, GWD was deeper in the upper subsection of each field, which might oxidize sulfides in the upper field subsection increasing the production of acidic discharge and affecting the overall pH of discharge water. This behavior of the field was not considered in the 1D model. The heterogeneity of the soil and GWD was not taken into account with the 1D model. Two- and three-dimensional models can simulate the spatial generation of DD and result in appropriate pH.

According to the measurements, DD was occasionally recorded when observed GWD was below the drain depth (1.1 m). The HAPSU model did not simulate DD when the GWD was below the drain depth in ND or weir depth in the CD. The correlation between GWD and pH of DD were not clearly observed based on measured values as NSE values of simulated pH against measured pH of DD were lower than zero. Based on the field topography, the slope of the field might have affected the hydrological process of the field. Also, it is important to keep in mind that GWD is point measurement.

Controlled drainage is noted as a possible solution to control outflow and reduce the loss of nutrient as well as maintaining the GWD (Gilliam and Skaggs, 1986). The Söderfjärden results (e.g., Figure 15) indicate that water management practices maintain the higher pH of discharge to some extent although the effectiveness of the controlled structures was not as notable as the theoretical description. Bronswijk et al. (1995) mentioned that in case of partial oxidation of the sulfidic material in the soil, only part of acidity will be transported to soil water and to DD, which could possibly dilute the DD because part of acidity retains in the soil, for example precipitation of jarosite. Part of acidity of water from the high subsection might be buffered with DD with higher pH from low subsection before released to drainage. To understand the behavior of soil heterogeneity and its impact on DD water quality, the 1D model might not be suitable. To understand the behavior of quality of DD, it would be important to divide the field into subsections and use the 2D chemical model in sloping AS agricultural field.

5.3.2. Effect of dredging and plastic sheet on water balance

Plastic sheet to separate the field sections was to prevent the bypass of groundwater between different fields and restrict the seepage (Österholm et al. 2015). Toivonen (2012) mentioned CD as a possible solution for maintaining acidity of soil in AS soil but there was no clear relationship between GWD and DD because of bypass groundwater flow in the soil profile in his study. The plastic barrier was proposed in his study to control bypass flow between the field and seepage to the main ditch. Österholm and Rosendahl (2012) noted that after the implementation of the plastic sheet, 50 mm water was necessary during the summer period in the same research field to avoid deepening the GWD below the critical layer in CDI field sections. Österholm and Rosendahl (2012) showed that the plastic sheet had a clear effect on the pumping rate, but the results in this study indicate that some seepage below the drain depth was still occurring. Overall water balance computation and GWD dropping below the drain depth during winter periods indicates additional flow path between field section and seepage from field to main ditch. After the implementation of plastic to control the bypass flow between the field sections, there was still a loss of water from the study field due to seepage (Figure 14). The higher measured DD for CD field than ND field in this study indicates plastic sheet was not fully functional to control the bypass flow between the field sections. The model simulations did not take into account the plastic, but the model was calibrated, and the estimated seepage volume would be equal to missing part of water balance. The dropping of GWD below the drain depth and plastic sheet indicated that seepage occurred even with the plastic sheet.

In the study of Österholm and Rosendahl (2012), seepage was observed from field sections to the main ditch before the plastic sheet was installed. They concluded that the main part of seepage occurred through preferential flow pathways, macropores, and soil cracks. Dents and Pons (1995) showed that the saturated hydraulic conductivity of acid sulfate soil changes over time due to the oxidation process of AS soil. Due to high potential evapotranspiration, the dropping of GWD to PASS layer ripens the soil structure and leaves permanent cracks in soil (Pons and Zonneveld, 1965). In Söderfjärden experiment field, GWD dropped to the critical layer during summer and winter and this could have changed in soil structure over the long period of time. The dynamic structure of AS soils could have increased preferential flow and seepage from the field to the main ditch.

The result of water balance (Figure 14) showed that the dredging of the main ditch in 2015 increased the missing part of the water balance. The increasing depth of the main ditch (Equation 12) increased the hydraulic head difference resulting higher seepage. The measured deepest GWD was in 2016 after the dredging (Figure 10; Figure 14). The average GWD during the winter and summer have deepened after dredging the main ditch. Deeper GWD and decreased DD after 2015 indicates increased additional water flow from field to main ditch. Seepage to the main ditch can be an important water flow pathway even in the flat field with the plastic barrier. Seepage can contribute to environmental loading and acidic discharge into the main ditch. In many studies, the leaching of harmful substances through seepage was not considered, but it can still be an important solute transport pathway (e.g., Turunen et al. 2015; 2013).

5.4. Model uncertainty

5.4.1. Drainmod-based model

The meteorological data for estimating potential evapotranspiration came from various sources. Some of the variables were measured close to the field. For computation of the global radiation parameter, the fraction of extraterrestrial radiation reaching the earth on a clear day was calibrated and validated with measured solar radiation data of Seinäjoki FMI weather station. Determining the parameters for computation of downward solar radiation in Vaasa with Seinäjoki dataset could possibly result in uncertainty in potential evapotranspiration.

Based on measured DD, there were events for negative discharge. This negative discharge indicated the water level in the main ditch was likely high and water was discharged from the main ditch to the subsurface drains. The possibility to set the boundary condition for seepage based on the water level in the main ditch could balance the equal volume of missing part of water balance in Figure 14.

For modelling CDI field, it was assumed the pumped water volume was equally distributed to the field section assuming the flat field. The experimental field has 0.14% of slope and irrigation through the drain pipes could be affected by the topography. Graphical observation in Figure 10 shows that the impact of sub-irrigation on measured GWD is higher than simulated GWD. The weir level scenarios showed that duo to the slopping field the pumped water affected highly the field section close to the control well. The distance between the controls wells is around 250 m. The effective range of the weir to dam water could be less effective on maintaining GWD because of elevation difference. So distributing the pumped water evenly throughout the field without considering the elevation difference might reduce the model performance for the 1D model.

Drainmod did not include the description for preferential flow. However, macropores and large cracks were observed in the study site (Österholm and Rosendahl, 2012). Introducing macropores, and shrinkage sub-model in the model and lateral movement of water taking into account topography with 2D or 3D could possibly improve the model performance for simulating field hydrology.

5.4.2. HAPSU model

Similar uncertainties were present with HAPSU model as with the Drainmod-based model. The important issue with HAPSU was observed with evapotranspiration, as it was much higher in the HAPSU simulations compared with the Drainmod-based model. Winter evapotranspiration and disregard of crop coefficient in HAPSU model increased the simulated evapotranspiration compared to drainmod-based model simulation. In reality, the weir depth changed between winter and summer periods. In HAPSU, the used weir depth was taken from the winter period.

The HAPSU model did not include the description for groundwater outflow (seepage) beneath the drain depth, which was likely one reason why the model overestimated DD and underestimated GWD. HAPSU model performance could possibly have improved with the change in parameterization and inclusion of seepage process. In HAPSU model, normal subsurface drainage equation with seepage with constant weir depth resulted in higher DD for CD and CDI fields. Similar behavior was observed in Figure 11, HAPSU model overestimated the peak DD for all field sections. Using the modified Hooghoudt drainage equation for CD field could underestimate the DD volume and peak event. Implementing sub-irrigation sub-model could possibly improve the model performance simulating the field hydrology with CDI practice rather than summing pumped water and precipitation as input precipitation to the field in HAPSU model. The total volume of precipitation with dynamic rainfall and snowfall correction factor in HAPSU model was higher compared to Drainmod-based model. Considering soil property changes over the study period and as the result of shrinkage, the cracks/macropores in the ground are not completely recovered as oxidation of AS soil could leave irreversible cracks in soil (Dents and Pons, 1994).

6. Conclusion

The drain discharge (DD) and groundwater depth (GWD) of three field sections with different water management practices were simulated using Drainmod-based and HAPSU models. Both models were suitable for describing the main hydrological processes in acid sulfate (AS) soils. Modelling proved to be an efficient tool for analyzing the field hydrological process and water quality under different water management practices. The measurements in the controlled drainage (CD) field section suggested that CD may not have the desired effect on water balance as total discharge volume is higher than normal drainage (ND) field section in our study field. Based on the model performance criteria, it appears the Drainmod-based model had better performance for simulating field hydrology due to its flexibility to implement processes and imply actions applied in the field, such as the change in weir depth, and dredging the main ditch. Therefore, the Drainmod-based model had satisfactory performance for CD and CDI field over HAPSU model. The model simulation demonstrated how CD reduced DD and controlled GWD. With continuous measurements, the impact of the weir/control well on CDI was observed, but the impact on maintain GWD was weaker than in the simulation.

The Drainmod-based model was calibrated against ND field data for 4 years and validated for 3 years. The model was validated also against CD and subsurface irrigation (CDI) field for seven years. Comparison of simulation results of both models with measured variables demonstrated that the impact of water management practices on field hydrology were not following theoretical descriptions. The HAPSU model suffered from missing seepage component representation for CD and CDI. HAPSU model simulated the ND field with satisfactory NSE values when water loss occurring through seepage was compensated by simulated evapotranspiration during the winter. The water management practices had no significant effect on simulated evapotranspiration. In Nordic conditions, the dropping of GWD below drain depth during the winter period might be the indication of seepage. Here 1D models simulated the main hydrological processes of an agricultural field without considering the topography of the field. However, the study showed that topography of the field might affect the performance of CD and CDI. Without the implementation of the topography of the field, it was not possible to understand horizontal water movement and its impact on GWD in the lower field subsection. With the implementation of macropores, soil shrinkage and topography with 2D or 3D, the performance of both models for simulating field hydrology could be improved

The impact of the dredging and control structure on DD and GWD was seen in the water balance study. With increased missing part of water balance after dredging and deeper annual GWD indicates the impact of CD and CDI was less effective because of seepage. In this study, based on measured GWD, effectiveness of the control structure to maintain GWD was weaker due to field topography and the dredging of the main ditch. Deeper average GWD during summer period after 2015 indicates dredging increased preferential flow path of groundwater to main ditch or between the field sections. One option to improve controlling GWD in the field would be to reduce the seepage from the field to the main ditch by controlling the water level in the main ditch. To understand the behavior of the field operations, flexibility for adding the hydrological process to the model can improve the simulation result. In general, the comparison model revealed that implementation of seepage (discharge to main ditch) enhances the prediction of GWD in the studied field.

Based on both measured and simulated pH of DD, fields with controlled structure had a positive impact for maintaining pH higher than in ND field. Simulated water quality of DD in HAPSU model was affected by soil properties of each soil layer. Maintaining GWD prevents the oxidation of sulfidic material and helps to increase the pH of DD. Variation of GWD across the field section made it difficult to estimate the quality of water as oxidation of sulfidic materials may not be consistent across the field. The water quality modelling in HAPSU could be improved if topography and its effect on GWD and soil pH were described. HAPSU model could be updated for the hydrological and geochemical part with current knowledge of AS soils type. Further development of both models for AS soils, the spatial variability of GWD and formation of acidic discharge requires a 2D or 3D model.

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Appendix A

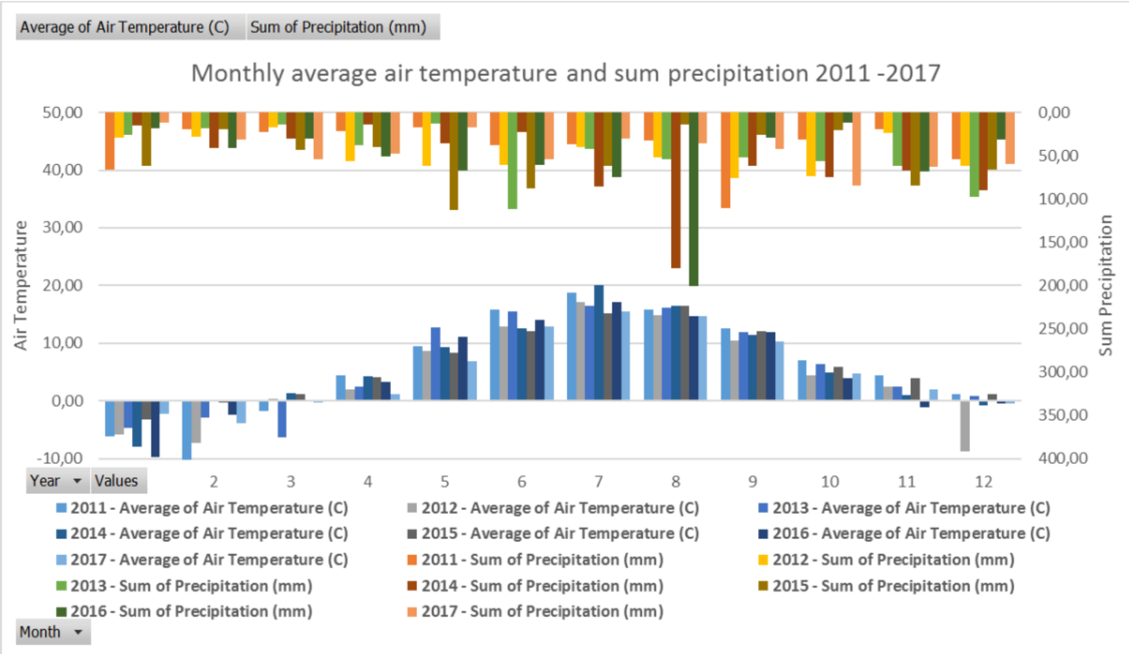

Figure A1. Monthly average Air Temperature for study field.

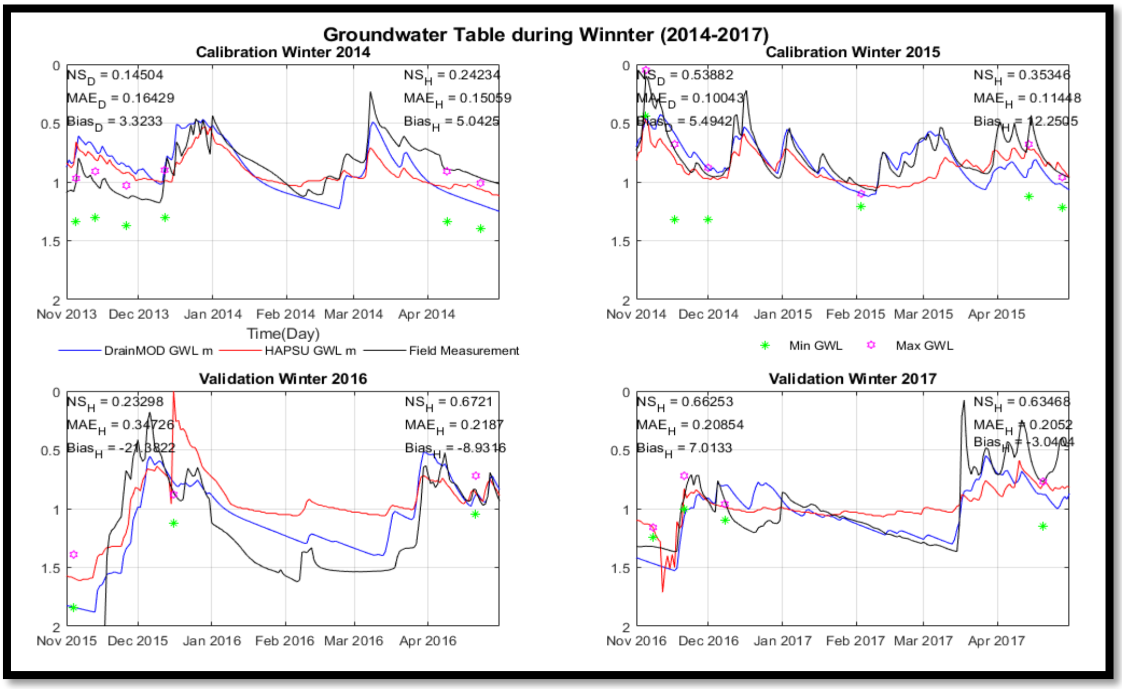

Figure A2. Model Performance during winter period for ND field section

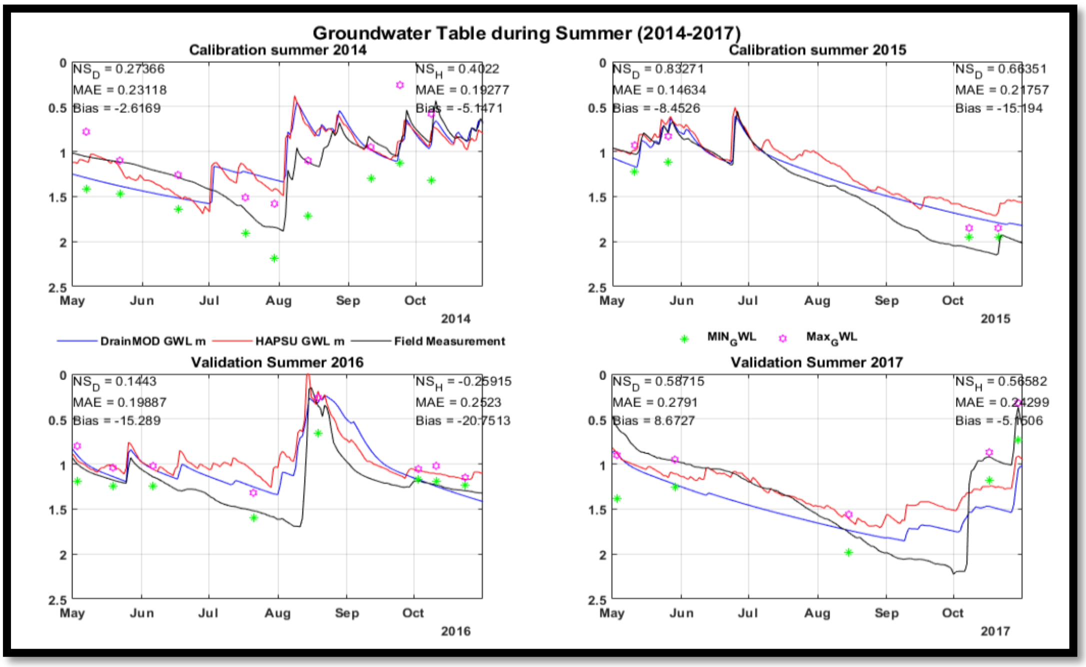

Figure A3. Model Performance during winter period for ND field section.

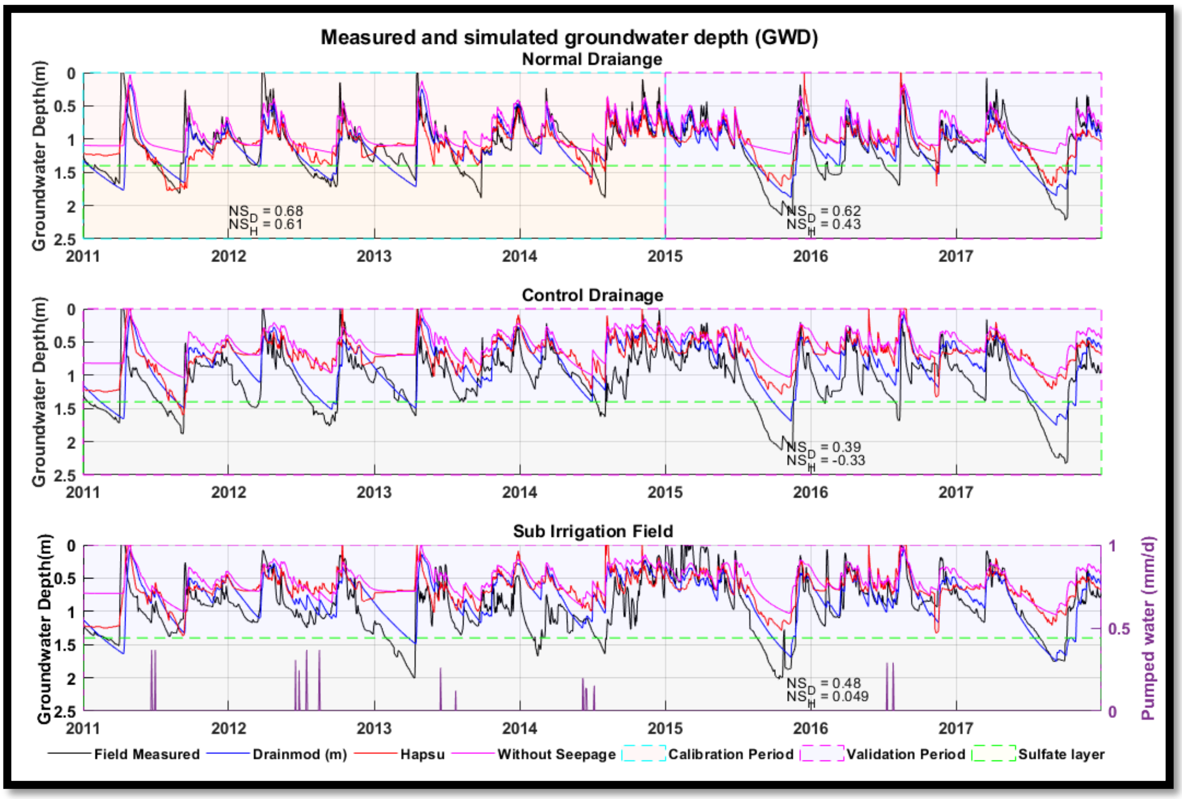

Figure A4. Calibration and validation of models with and without seepage outflow compenent in Drainmod-based model.

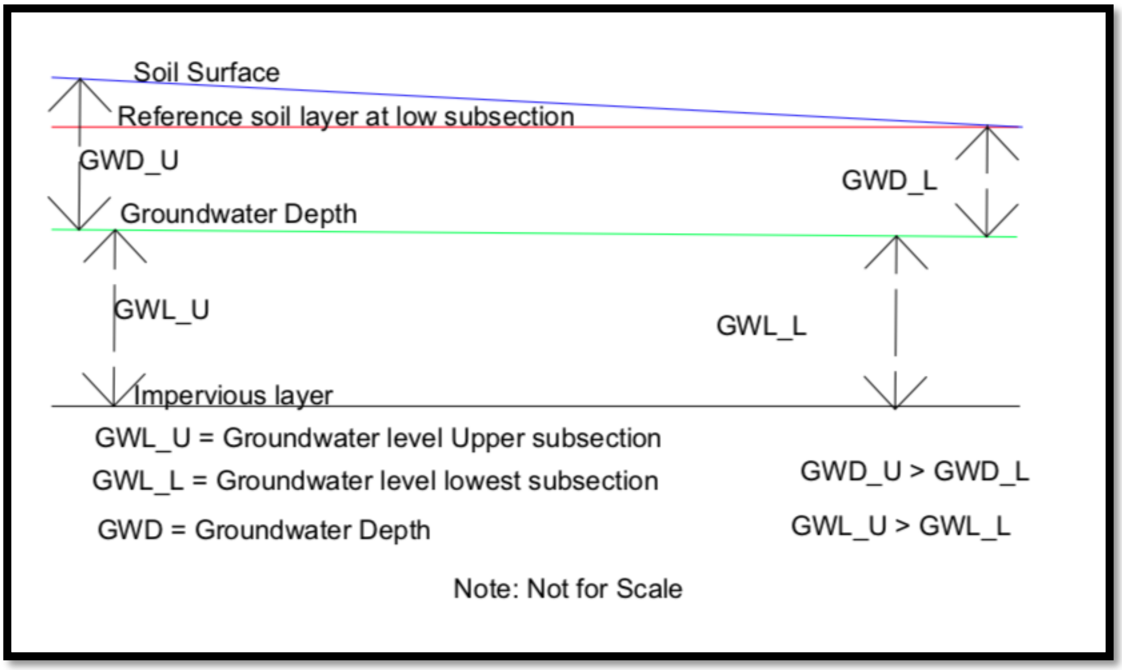

Figure A5. Schematic drawing of groundwater depth (GWD) and groundwater level (GWL) profile observed based on field measurement.

Table A1. Measured soil properties of experimental field.

Layer (cm)	0-50	50-100
Θs (m^3/m^3)	0.4215	0.3801
Θr (m^3/m^3)	0.0591	0.3243
α (1/m)	0.0143	0.0151
n	1.0455	1.3253
Ksat (m/h)	0.0004	0.0002